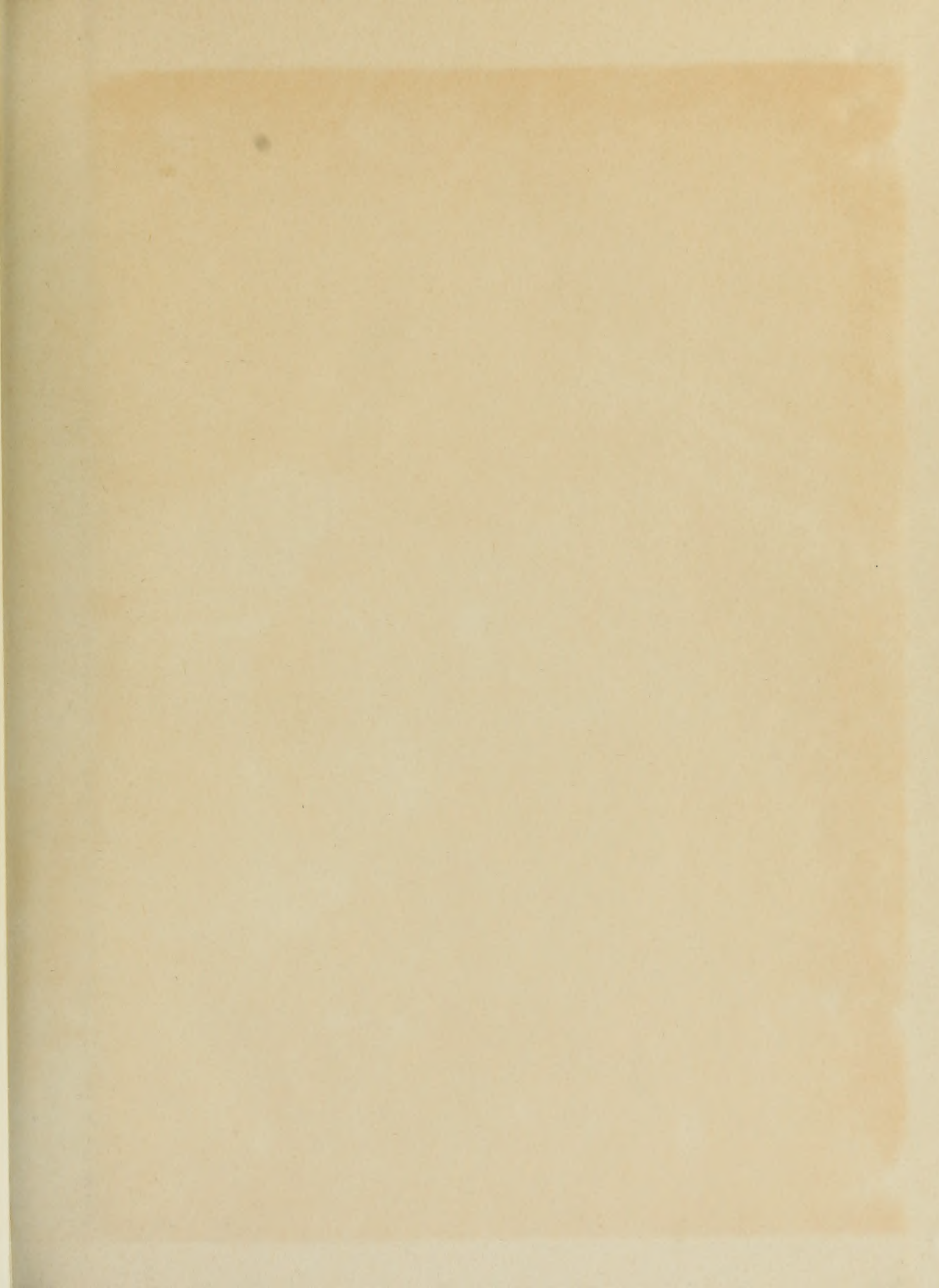


INVESTIGATION OF ROTATING STALL
IN A CENTRIFUGAL VANED DIFFUSER

Frank Tafe Hemler
and
Calvin Yuke Sing







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Letter on front cover:

INVESTIGATION OF ROTATING STALL
IN A CENTRIFUGAL VANED DIFFUSER

Frank Tafe Hemler
and
Calvin Yuke Sing

Cambridge, Massachusetts
May 24, 1954

Professor L. F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering, we herewith submit a thesis entitled "Investigation of Rotating Stall in a Centrifugal Vaned Diffuser".

**INVESTIGATION OF ROTATING STALL IN A
CENTRIFUGAL VANED DIFFUSER**

by

FRANK TAFE HEMLER

**B. S. A. E., United States Naval Postgraduate School
(1953)**

and

CALVIN YUKE SING

**B. E., University of Toledo
(1948)**

**SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF
SCIENCE**

at the

**MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 1954**

INVESTIGATION OF ROTATING STALL IN A CENTRIFUGAL VANED DIFFUSER

by

FRANK T. HEMLER, LT. U.S. NAVY

and

CALVIN T. KING

Submitted to the Department of Aeronautical Engineering on
24 May 1954 in partial fulfillment of the requirements for
the degree of Master of Science in Aeronautical Engineering.

SUMMARY

There is a definite need for information on rotating stall. Although some investigations have been made on cascades and axial compressors, very few investigations have been made with centrifugal compressors. Further, the present theory concerning the causes of rotating stall are still somewhat nebulous. Therefore, investigations were carried out with a centrifugal vane diffuser.

The flow in the centrifugal vane diffuser was studied with barium titanate crystals and tufts. The mass flow, pressure, velocity, solidity factor, angle of attack and blade types were varied in the test section in order to obtain as much information as possible.

No rotating stall was encountered at any of the conditions investigated. Due to the results of these experiments, it was decided that the present theory is incomplete. Recommended future investigations should include:

- (1) a dimensional analysis attack on the problem.

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- (2) The study of the flow in a centrifugal diffuser with flat plates. Each plate should be out of the stalled region of adjacent plates.
- (3) The study of rotating stall as produced by the British in one of the references.
- (4) The further study of the flow in a centrifugal compressor with blades of gentle stall characteristics.

These investigations were accomplished by two graduate students, Lt. Frank T. Hemler, U. S. Navy, and Calvin Y. Sing at Massachusetts Institute of Technology's Gas Turbine Laboratory, Cambridge, Massachusetts.

Thesis Supervisor:
Title:

E. S. Taylor
Professor of Aircraft Engines

The people of the State are entitled to know the truth about the situation in the State and to be able to judge for themselves.

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INVESTIGATION OF ROTATING STALL IN A CENTRIFUGAL VANED DIFFUSER

DEFINITIONS USED IN THIS THESIS:

ROTATING STALL -- Intermittent partial or complete stalling of one or more blade passages of a compressor wherein the stalled portion rotates around the wheel in a tangential direction and the flow far upstream and far downstream of the wheel is unaffected.

STALL-FLUTTER -- Self-excited vibration of blades together with stall, such that there is coupling or feedback from flutter to stalling and unstalling, and from stalling and unstalling to flutter.

SURGE -- An audible pulsation of compressor pressure rise and weight-flow rate, wherein the flow far downstream and far upstream of the wheel has the same periodic pulsations of flow as are heard at the compressor.

THEORY OF THE FLOW OF FLUIDS IN A PIPE

BY J. H. P. VAN DER MEER

DEPARTMENT OF MECHANICAL ENGINEERING

UNIVERSITY OF TORONTO, CANADA

AND TO THE HON. CHIEF OF DEFENSE

DEPARTMENT OF DEFENSE, CANADA

REPORT NO. 1000

1960

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1960

I. INTRODUCTION

Recent investigations have shown that malfunctioning and structural failure of compressors, formerly attributed to stall-flutter and surge, have indeed been caused by rotating stall.

Stall-flutter has been investigated by Sisto, Ref. 1 and Schnittger, Ref. 2. More recently, Emmons in Ref. 3 has investigated compressor surge and stall phenomena. Huppert and Benser in Ref. 4 show the results of studying rotating stall in an axial compressor.

The more recent investigations have shown that some compressor acceleration difficulties are attributable to rotating stall. Even more important, blade failures and complete structural failures have resulted from rotating stall.

It is imperative, therefore, to know when, where, and under what conditions rotating stall will occur.

Present knowledge of rotating stall consists of:

- (1) Its definition.
- (2) Observed tests in cascades and axial compressors -- both single and multi-staged.
- (3) The not disproven theory that rotating stall is due to inertia effects of air flow in the passages and a time lag from

goldfish, which made a few days later the 100th anniversary of the

-Link to Internet directly: <http://www.irs.gov> is useful directory site.

Revised and enlarged. First edition published by Collins 1966.

1. *Leitungsstellen und Abteilungen* (Leitung und Mitarbeiter)

— *Journal of the American Medical Association*, 1947, 135: 1041.

Source: *U.S. Census Bureau, Current Population Reports*.

blade stall until the upstream fluid feels the effect of that stall.

There is a dearth of material regarding rotating stall in centrifugal machines, although the British report one instance of it in Ref. 5. In an effort to accumulate evidence for more analytical studies, the flow through a centrifugal vaned diffuser was observed in this study. Conditions of angle-of-attack, mass flow, pressure in the passages, velocity, solidity factor and blade types were varied during this investigation.

The broad purposes of this thesis are two-fold:

- (1) To verify or nullify present theory as to the nature of rotating stall by the study of centrifugal flow and subsequent comparison with axial flow and cascade data.
- (2) To prepare the groundwork for future analytical or laboratory studies of the phenomena, and to indicate the desired direction for these future investigations, by accumulation of data concerning rotating stall.

This investigation was accomplished by two postgraduate students at M.I.T.: Lt. Frank T. Hemler, U. S. Navy,

It is a very common mistake to suppose that the

only way of getting rid of a disease is by

treating it with medicine. In fact, the best way

of getting rid of a disease is by getting rid of the cause of it.

For example, if a person has a cold, the best way

of getting rid of it is by getting rid of the cold virus.

This can be done by using a cold remedy.

There are many other diseases which can be

got rid of in this way.

The following are some of the diseases which

can be got rid of in this way:

(1) The common cold.

(2) Influenza.

(3) Whooping cough.

(4) Measles.

(5) Rubella.

(6) Mumps.

(7) Chickenpox.

(8) Shingles.

It is

very important to get rid of these diseases as soon as

possible, as they can cause serious complications if not

attached to the U.S. Naval Postgraduate School program, and Calvin Y. Siag, both of whom were working towards their Science Master degree in Aeronautical Engineering. The investigations were accomplished in the Gas Turbine Laboratory of M.I. T. during the period of September 1933 through May 1934.

Thanks is expressed here to the thoughtful supervision, guidance, and suggestions made by Prof. E. S. Taylor of M.I. T.'s Gas Turbine Laboratory. Many other individuals in the Gas Turbine Laboratory and M.I. T. helped the authors tremendously.

1. The first part of the paper is devoted to the study of the
 properties of the function $f(x)$ defined by the equation

$$f(x) = \int_0^x \frac{1}{1+t^2} dt$$
 for $x \in \mathbb{R}$. It is shown that $f(x)$ is an odd function and
 that $f(x) \in C^1(\mathbb{R})$. Moreover, it is proved that

$$f(x) = \arctan x$$
 for all $x \in \mathbb{R}$. The second part of the paper is devoted to
 the study of the function $g(x)$ defined by the equation

$$g(x) = \int_0^x \frac{1}{1+t^4} dt$$
 for $x \in \mathbb{R}$. It is shown that $g(x)$ is an even function and
 that $g(x) \in C^1(\mathbb{R})$. Moreover, it is proved that

$$g(x) = \frac{1}{3} \arctan \frac{x}{\sqrt{1-x^2}}$$
 for all $x \in \mathbb{R}$. The third part of the paper is devoted to
 the study of the function $h(x)$ defined by the equation

$$h(x) = \int_0^x \frac{1}{1+t^6} dt$$
 for $x \in \mathbb{R}$. It is shown that $h(x)$ is an odd function and
 that $h(x) \in C^1(\mathbb{R})$. Moreover, it is proved that

$$h(x) = \frac{1}{5} \arctan \frac{x}{\sqrt{1-x^2}}$$
 for all $x \in \mathbb{R}$.

REFERENCES

II. EQUIPMENT

The Centrifugal Vaned Diffuser

The major component used in these tests was a centrifugal vaned diffuser. This type of diffuser was studied rather than a cascade in order to allow the flow to reenter upon itself. Further, a cascade study would not maintain the desired conditions long enough for full investigation. The exterior of the set-up as used in M.I. T.'s Gas Turbine Laboratory is shown in Figs. 1 and 2.

Construction details of the centrifugal diffuser used can be found in Appendix A. As can be seen in Appendix A and Fig. 1, it is possible to vary the angle of flow.

The angle of flow as used in this report is that angle measured between the flow and a tangent to the inlet circle of the diffuser section. Rotation of the nozzle blades varies the departing flow angle from ten degrees to twenty degrees, as shown in Fig. 3. This variation allows different angles of attack for the stationary test blades.

The test blades are permanently in place when once inserted in the blade ring. Appendix A and Figs. 4 and 5, show that the entire blade ring with blades installed can be removed from the test rig. Figs. 6, 7, and 8 show the blades that were

The Chemistry of the Atmosphere

The subject of atmospheric chemistry is one of the most important in the study of the atmosphere. It is a branch of chemistry which deals with the chemical composition of the atmosphere and the changes which take place in it. The study of atmospheric chemistry is of great importance in the study of the atmosphere as a whole. It is a branch of chemistry which deals with the chemical composition of the atmosphere and the changes which take place in it. The study of atmospheric chemistry is of great importance in the study of the atmosphere as a whole.

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used in the experiments covered by this report. The blades themselves are discussed later in this section. The blades shown in Fig. 6 were milled out of a solid aluminum ring. They are integral with the blade ring. The blades shown in Figs. 7 and 8 were machined individually. After making the blade forms, two holes were drilled in the sides. Pins of #29 drill rod were inserted into these holes with a press fit. This left the blades with two pins projecting from the sides, as shown in Figs. 7 and 8.

Another blade ring was made out of steel. Holes were drilled into the steel blade ring to match the projecting pins of the blades. In this manner, the blades could be inserted and removed at will, but a press fit insured against accidental removal. Also, as the test section is brought up flush with the cover plate as described in Appendix A, no flutter of the blades is possible. The cover plate and test section (blades) are held together by the force of the thrust nut.

The angle of attack of the blades shown in Fig. 7 and the angle of incidence of the blades shown in Fig. 8, was 14.1 and 15 degrees, respectively. These angles were incorporated in the blade ring. The flow angle and the angle of attack (or angle of incidence) were additive as shown in Appendix B.

Three different sets of blades were used. The first set used was the one shown in Fig. 6. Shape details of this set of blades can be found in Fig. 9. These blades are used in the General Electric C-14 diffuser. The second set of blades were blades of the form NACA 65-(12) 10 transformed from rectangular cascade form to a circular diffuser cascade. Fig. 7 shows the transformed blades. Appendix B shows how the rectangular cascade was transformed into the circular diffuser by means of conformal transformation. Ref. 6 gives a development of the method and equations used in this conformal transformation. The third set of blades were flat plates as shown in Fig. 8. These flat plates were milled with all edges sharp.

The Gas Turbine Laboratory and Facilities

The Gas Turbine Laboratory is an integral part of M.I. T., situated on its campus in Cambridge, Massachusetts. One part of this laboratory's equipment is a De Laval Air Compressor made by the De Laval Steam Turbine Co., Trenton, N. J. This compressor is run by a General Electric a. c. motor. The compressor is rated at 15,500 cuft per minute discharge, 5.33 psia suction pressure, 16.0 psia discharge pressure, 700 brake horsepower, at a compressor speed of 4600 RPM. Fig. 10 is a line diagram of the test set-up, showing necessary valves, gauges

and piping. Lines to and from other equipment serve such things as a small supersonic tunnel, etc. These other pieces of equipment were isolated for any run. Gauges and lines necessary to run the compressor, but unimportant to the experimenter are not shown in Fig. 10. Gauges shown are total temperature and total pressure gauges. Lines to and from the test diffuser are eight inch pipes.

Instrumentation and Reading of the Test Set-up

From the readings of RPM, pressures, and temperatures, it was possible to compute the operating point on the compressor map shown in Fig. 11. Fig. 11 also shows how to compute the factors necessary to establish that point. The mass flow and the velocity at any point in the test set-up could be computed.

It was necessary to: (1) distinguish between surge and rotating stall, (2) establish the speed of rotation, if rotating stall occurred, (3) establish the size of the rotating stalled region and (4) establish the number of stalled regions around the diffuser perimeter. It was also desirable to look at the flow in the channels in order to obtain some idea of what was happening and where.

The authors decided to meet the first three problems by using barium titanate crystals spaced at angles of 0, 72.5, and 180 degrees. These angles were chosen to give positive

identification of the stalled regions. Radially, the crystals were placed at 8.5 inches. This distance put the crystals in blade passages near the upstream end of those passages. It also enabled the crystals, which are one-half inch in diameter, to be placed so that no blade touched the crystals.

Some tests made on the crystals by the authors are included in Appendix C. These test results showed the suitability of the crystals for these experiments. The crystals were pressed into brass plugs of three-quarter inch outside diameter, which, in turn, were centered at the positions already indicated. Shielded leads went from the crystals to a RCA Cathode Ray Oscilloscope No. 160-B. The leads were run in parallel. The leads from the crystal at the 72.5 degree position were reversed in polarity for further identification. Of the first three problems previously outlined, the set-up as stated eliminated these problems as follows:

- (1) Rotating stall would appear as shown in Fig. 12a, while surge would appear as in Fig. 12b. In other words, surge would occur at even intervals, while rotating stall would be at uneven intervals, due to the arrangement of the crystals.

- (2) Regarding the speed of the stalled re-

...the ... of ...

1. The first of these is the fact that the Commission has not yet received any information from the Government of the United Kingdom regarding the proposed amendments to the Bill. It is therefore unable to comment on the merits of the proposals at this stage.

gion -- should rotating stall be encountered, it would be only necessary to impose a known frequency on the oscilloscope, and measure the ratio between the known and unknown. Then, knowing the geometry, the speed could be determined.

- (3) The size of the stalled region can be measured from the elapsed time for the stalled region to pass one crystal. The time would be measured by comparison with a known frequency.

In order to solve problem (4) and to observe the flow, a 2 1/2 inch diameter observation plate was made of plexiglass. This plate was pierced eccentrically with a wire which held many strings to be used as tufts. The observation plate is shown in Fig. 13. A matching hole was drilled in the front cover plate into which the observation plate fitted. Fig. 1 shows the observation plate in place, held by a shoulder of the plate and two brackets. The eccentricity of the tufts allowed them to be rotated, while the blades and back plate could be loosened and rotated. These two variables allowed the whole field of the vaneless diffuser to be

the economy, the speed would be as-

(3) The size of the swollen region can be measured from the elapsed time for the swollen region to pass over a fixed. The time would be measured by comparing with a known frequency.

various other the whole field of the vessel or vessel to be

observed. Problem (4) was solved for slow speed rotation by observing the tufts and for high speed rotation by angularity relations of the crystals and a known frequency.

III. PROCEDURE

During the course of these investigations, the crystals were polarized twice as described in Appendix C. This was done to keep the crystals accurate and reliable. Six crystals were polarized and three crystals were selected by testing on the oscilloscope for equal deflections from a constant tone. The selected crystals were placed in the brass plugs, and mounted in the front plate. An ohmmeter was then used on each of the leads to ascertain that there were no shorts and no leads were grounded. The leads were hooked to the oscilloscope as shown in Fig. 1 and again checked with an ohmmeter.

The test rig was assembled as shown in Appendix A. The tufts were inserted as shown in Fig. 1. A final check with the ohmmeter on the crystal leads was then made. Prior to each run the local temperature and barometric pressure were recorded.

During Each Run

After opening the outlet and inlet valves of the test rig, the laboratory mechanic brought the De Laval air compressor

up to the desired operating point. This desired operating point was obtained as follows:

- (1) The compressor was brought to an RPM thought to be correct.
- (2) Closing of the atmospheric inlet valve isolated the system.
- (3) Readings of P_{o1} , P_{o2} , T_{o1} , and RPM were taken.
- (4) As shown in Appendix D, the actual operating point on the compressor map was then calculated.
- (5) From the actual operating point, adjustments were made to the RPM and by-pass valve until the desired operating point was obtained. This was done by trial and error, calculating each intermediate operating point as steady-state conditions were attained.

This desired point was chosen from the compressor characteristic map. The flow angle desired was set at the test rig.

The above conditions were held while the oscilloscope was surveyed from five to five thousand cycles. Then the passages

the first of these elements is the element α of the set A .

the second of these is the element β of the set B .

the third of these is the element γ of the set C .

the fourth of these is the element δ of the set D .

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the element β of the set B is the element γ of the set C .

(2) the element α of the set A is the element γ of the set C .

the element γ of the set C is the element δ of the set D .

(3) the element α of the set A is the element δ of the set D .

the element δ of the set D is the element α of the set A .

the element α of the set A is the element δ of the set D .

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the element α of the set A is the element δ of the set D .

This last point was shown to be the case by the above argument.

the element α of the set A is the element δ of the set D .

the element δ of the set D is the element α of the set A .

the element α of the set A is the element δ of the set D .

were surveyed with the tufts in the observation plate.

Maintaining the same operating point on the compressor map, a different flow angle was selected. Again, survey of the oscilloscope ranges and a survey at the blade passages with the tufts were made. The same procedure was carried out until all the desired flow angles were checked. At this point, another operating point on the compressor map was chosen. The same procedure outlined above was carried out for the new operating point. The above procedure was repeated until all the desired operating points were checked with each set of blades.

In order to check on the solidity factor, the runs made with 36 of the NACA blades were repeated with every other blade removed.

After each run, when the compressor was shut down, the crystal leads were checked with the ohmmeter for continuity. Each crystal was individually checked to make certain it was still operating correctly.

The order of blades used was:

- (1) C-14 blades -- Fig. 6
- (2) NACA blades -- Fig. 7
- (3) Flat plates -- Fig. 8

Generally speaking, for each set of blades, the

was removed with the bolts in the observation glass.

including the same opening point on the same

system with a different flow rate and different. Again, every
of the microscope target and a survey of the glass passage with

the same result. The same procedure was carried out until

all the tested flow rates were observed. At this point, however,

opening point on the microscope was not observed. The same

procedure followed above was carried out for the new opening

point. The above procedure was repeated until all the points

opening points were checked with each set of plates.

In order to check on the existing factor, the same

work was done in the same place with different sets of plates.

plate removed.

After each run, when the compressor was shut down,

the system was checked with the same set of plates.

Each system was individually checked in order to be sure that

opening correctly.

The order of plate on each was

(1) C-12 plates -- 1/2, 1

(2) XACA plates -- 1/2, 1

(3) 1/2 plates -- 1/2, 1

consequently, the same set of plates was

same points on the compressor map were investigated. Table I lists the operating points used. Slight variations from these points occurred for two reasons:

- (1) As the nozzle blades were opened or closed, the mass flow was altered slightly. This altered the pressure ratio and mass flow factor. Checking on the operating points when the nozzle blades went from full opened to full closed altered the operating point so little that the change could not be plotted.
- (2) It was very hard to obtain the exact same point in two different runs with the air compressor. Arbitrarily, it was decided that a variation of 0.025 in the mass flow factor and 0.05 in the pressure ratio, on the compressor map, would be considered the same point.

For each operating point, the flow angles set were 10, 15, and 20 degrees.

Three "auxiliary" runs were made. One run consisted of finding what occurred when a blade was set over one of

Table 1. The effect of the concentration of the solution on the rate of reaction.

It is seen from the table that the rate of reaction increases with the concentration of the solution.

The results of the experiment are given in Table 1.

It is seen from the table that the rate of reaction increases with the concentration of the solution.

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10. 11. and 12. are given.

It is seen from the table that the rate of reaction increases with the concentration of the solution.

It is seen from the table that the rate of reaction increases with the concentration of the solution.

the crystals. The blades were placed over the crystals and the oscilloscope patterns were compared with the previous patterns when the crystals were in the passage. The second "auxiliary" run consisted of investigating the diffuser when the air compressor was surging. This operating point is point number nine of Table I. The third "auxiliary" run was made from operating point number 4, with the NACA blades. After the routine surveys, the exhaust valve from the test rig was closed down until the main air compressor surged. A survey was then made with the tufts and oscilloscope.

The original procedural plan of the authors' was to accomplish what is outlined above, until rotating stall was encountered. As soon as rotating stall was encountered further testing would be in the region of the rotating stall. This investigation would include pictures of the oscilloscope, patterns and tape recordings of any unusual sounds, in addition to that outlined above.

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IV. RESULTS AND DISCUSSION

Table I shows the nine operating points that were used. Placing these points on the compressor map, Fig. 11, shows that the points were chosen for the following reasons:

(1) Points 1, 2, 3, 4, 6, and 7 are just inside the surge line. This gave the maximum usable pressure ratio range from the air compressor.

(2) Points 5 and 8 were chosen to see if there were any peculiarity of upstream flow.

The oscilloscope patterns and tufts would then indicate unusual conditions or possibly rotating stall. In picking the points 5 and 8, it was appreciated that only the pressure ratio should effect the test set-up. This is because the guide vanes choked with high mass flow. This necessitated opening the by-pass valve shown in Fig. 10 in order to attain points 5 and 8. In effect, the compressor operated at points 5 and 8, but the test section operated at the same pressure

IV. RESULTS AND DISCUSSION

Table I shows the data reported before this work.

Using these points as the compressor was 17.5 in. diameter.

Two test points were chosen as the following reasons:

(I) Points 1, 2, 3, 4, 5, and 6 are best for

this test setup. This gives the most

complete picture of the test.

For the compressor.

(II) Points 7 and 8 were chosen to see if there

was any difference in operation.

The compressor pressure was held

constant throughout the test.

or possibly rotating stall in picking

the points 7 and 8 is not appropriate.

With this test pressure will remain about

the test set-up. This is because the

gauge vane choked with high mass flow.

This necessitated opening the by-pass

valve shown in fig. 10 in order to obtain

points 7 and 8. In effect, the compressor

operated at points 7 and 8, but the test

section operated at the same pressure.

and a lower mass flow.

- (3) Point 9 was chosen to investigate conditions during mild surge of the compressor.

Appendix D shows the calculations necessary to determine an operating point.

THERE WAS NO INDICATION OF ROTATING STALL AT ANY OF THE CONDITIONS INVESTIGATED.

Stall-flutter was effectively eliminated by the press fit of the blades into the blade rings on one edge, and by the force of the cover plate on the other edge. This system held the blades firmly along both edges, as shown in Appendix A.

Oscilloscope indications consisted mainly of random noise. At approximately 4,200 cycles a wave of sinusoidal form was noted. This wave form was present at every condition investigated. It was not the RPM of the compressor, since this varied. This sine wave was probably caused by a whistle in the piping. Because of the sinusoidal form, it was concluded that this wave had no bearing on surge or rotating stall.

Occasionally higher amplitude blips were noted. These were infrequent and had no recurrent pattern.

As shown in Sketch 1, the C-14 blades gave tuft indications of stalled and unstalled blades as the angle of flow was

There is a small hole in the

(2) Point 7 was found to be a small hole

Some testing with one of the compressors.

Approximate 10 hours for the testing to be

testing on a small scale.

There was no indication of rotating stall

at any of the conditions investigated.

Small holes were observed in the gas

in the place near the blade edge on the right and on the left

of the rotor blade on the right side. This is shown in the figure

which shows the right side of the rotor blade.

Small holes were observed in the gas

in the place near the blade edge on the right and on the left

of the rotor blade on the right side. This is shown in the figure

which shows the right side of the rotor blade.

This also shows the right side of the rotor blade.

Because of the small hole in the gas, it was concluded that this was

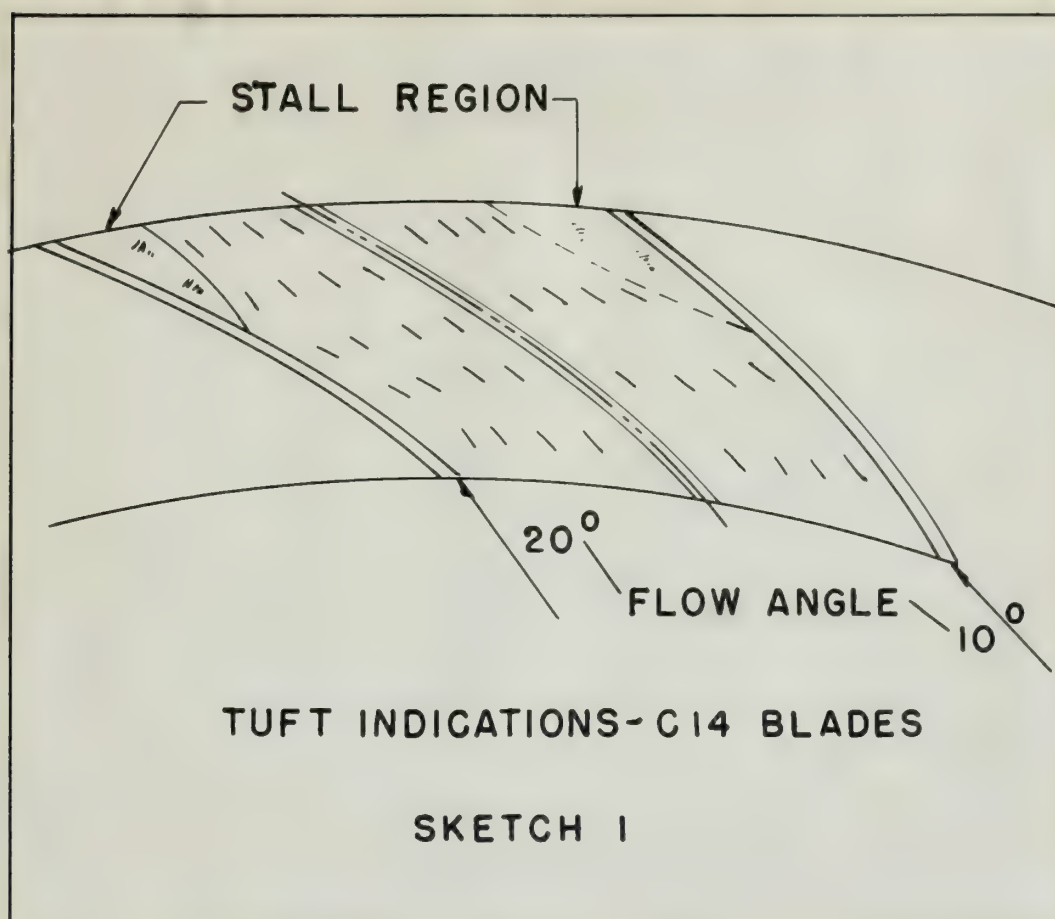
and no testing on a large scale was required.

Occasionally other small holes were noted.

There were no indications of rotating stall.

As shown in Sketch 1, the C-14 plane was cut in-

Sketch of the C-14 plane and showing the location of the holes in the gas.



varied from 10 to 20 degrees, respectively. The flow angle was shifted very slowly so that all blades went from the unstalled to the stalled condition. Nothing unusual occurred. The transition was quick and positive, regardless of how slowly the angle of flow was altered. While the blades were unstalled, but close to the stalling flow angle (approximately fifteen degrees), a brass rod was inserted into the downstream flow of the nozzle blades. It was hoped that the wake effect would stall one or more passages and that rotating stall would occur. It didn't.

effect was not observed until about 1900. It was
 found that the water level in the lake was
 rising very slowly, and that the water was
 becoming more and more brackish. The reason
 for this was the increasing population of the
 lake, and the increasing amount of water
 being poured into it. The water was becoming
 more and more brackish, and the water level
 was rising. This was due to the increasing
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 poured into it. The water was becoming more
 and more brackish, and the water level was
 rising. This was due to the increasing
 population of the lake, and the increasing
 amount of water being poured into it.

During the tests with the NACA 65-(12) 10 blades, the separation point remained very close to 1 1/2 inch from the trailing edge. It moved forward slightly at a flow angle of 10 degrees, but no more than 1/4 of an inch. It moved back a like amount at 20 degrees flow angle. This movement decreased to an imperceptible amount at low mass flows.

The blade passages were never completely turbulent with the NACA 65-(12) 10 blades installed.

When the solidity factor was varied by reducing the number of blades from 36 to 18, there was no change in any of the foregoing results.

With the flat plate installation, (even with 18 plates), the passages were turbulent all the time. This is attributable to the following sequence of facts:

- (1) The sharp leading edges made the separation point occur near the leading edge.
- (2) The flow angle was effectively 10 to 20 degrees.
- (3) (1) and (2) put each succeeding blade in the stalled region of the blade ahead of it.
- (4) Each blade and passage then became

During the tests with the 1000-12-1111 in place, the

repositioning of the 1000-12-1111 from the 1000-

1000 edge. It moved forward slightly to a new angle of 15 degrees.

For the tests with 1000-12-1111 in place, it moved back to the original

to replace the angle. This movement occurred in an irregular

which caused it to move back.

The 1000-12-1111 was never completely isolated

with the 1000-12-1111 in place.

When the 1000-12-1111 was moved by rotating the

1000-12-1111 from 15 to 10, there was no change in any of the

measured results.

With the 1000-12-1111 in place, there was no change

the 1000-12-1111 was moved all the time. This is attributed to

the following reasons:

(1) The 1000-12-1111 was moved from the 1000-

1000 edge to the 1000-12-1111 edge.

(2) The 1000-12-1111 was moved from 15 to 10

degrees.

(3) The 1000-12-1111 was moved from 15 to 10

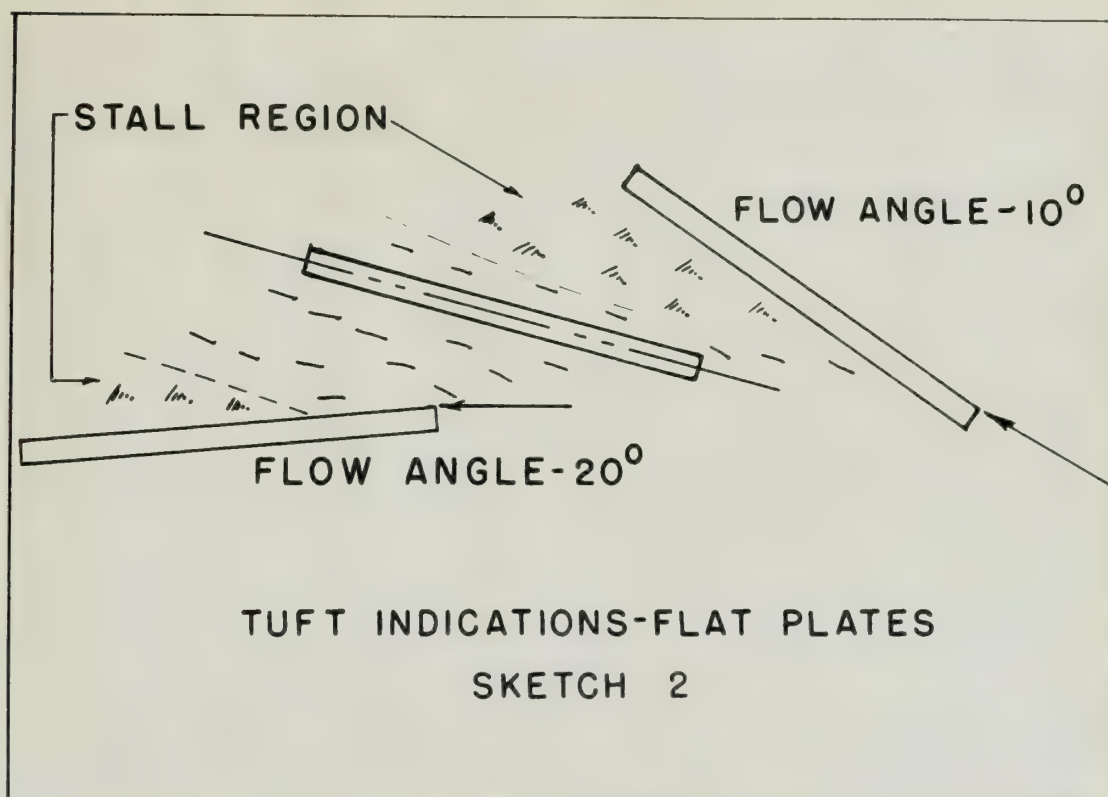
degrees.

11.

(4) The 1000-12-1111 was moved from the 1000-

fully turbulent.

With the flat plates installed, at low mass flow, the tufts indicated turbulent flow on the pressure side of the blade, as shown in Sketch 2.



This occurred at a flow angle of ten degrees. This phenomenon occurred only once and could not be repeated. No explanation is offered for its occurrence.

The C-14 blades were picked for these experiments for two major reasons. First, they are in use commercially.

Secondly, they were available at the beginning of these tests, which meant that the test set-up could be checked quickly as to its adequacy for this investigation. In addition, results of C-14 blade runs would give some clue as to the trend of experiments to be followed in the future.

Upon completion of the investigation of the C-14 blades, it was decided to try a NACA 65-(12) 10 blade. This blade reputedly had a gentle C_L - α curve near the stall point, as shown in Fig. 14a. This decision involved the present theory of rotating stall as explained in Refs. 3 and 4. For clarification, a quick review of that theory is presented here.

A rectangular cascade is formed as shown in Fig. 15. Assume an angle of attack, as shown, which is just below stalling; i. e., any increase in angle of attack will cause stalling. Further assume some small perturbation causes a transitory increase in the angle of attack of blade number 2. This causes blade 2 to stall. This stalling causes more low energy air in the passage. The high energy air now has less area to pass through. This partial blocking of passage B causes upstream air to be diverted to blade passages A and C. There is a time lag from the time the blade stalls until the upstream air feels this stall. The diversion of upstream air causes the angle of attack on blade number 3 to

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increase and on blade number 1 to decrease. This in turn will cause blade 3 to stall, while blade 1 is further away from the stall point. As passage C now diverts air to passages B and D, blade 2 tends to unstall and blade 4 to stall. Therefore, this stall can be seen to be progressing upward.

With rotating compressors, the motion of the wheel in Fig. 15 would be down. Recent experiments have shown the speed of rotating stall to be about 1/2 the wheel speed in the direction of rotation. The vectors of Fig. 15 represent this condition.

Going back to the gentle $C_{L-\alpha}$ curve of the NACA blades, it was reasoned that the best chance of floating back and forth between stalling and unstalling would occur when very small changes in lift produced a substantial change in the angle of attack. In other words, a small change in energy produced comparatively big changes in angle of attack. Data published by the NACA is readily available on many airfoils. Of these airfoils, the NACA 65-(12) 10 has a very gentle $C_{L-\alpha}$ curve.

Since the results of the NACA blades showed no rotating stall, it was decided to go to the opposite extreme. Consequently, flat plates were the next forms tried. These flat plates have a $C_{L-\alpha}$ curve something like Fig. 14b. Although separation occurred at the leading edge on the flat plates and the

whole passage was turbulent, no rotating stall was found.

Why was no rotating stall found at any time?

The present theory of rotating stall mentions inertia and time lag. Since these two phenomena are both inherent and unavoidable, they were present in this test section. The flat plates were stalled with the flow in the passages turbulent at every operating condition. The NACA blades did stall, but the flow in the passages was mostly laminar. The C-14 blades reacted in both of these ways, but under different conditions. With a flow angle of ten degrees, the C-14 blades were stalled and the passages turbulent. With a flow angle of twenty degrees, the C-14 blades were stalled with a negative angle of attack. Any condition, in between these extremes could be obtained by varying the flow angle. Laminar flow could be obtained between the extremes. Attempts to instigate a rotating stall were made by changing the mass flow, velocity, pressure, blade form, solidity factor, separation point and wake effects.

Could the failure to find rotating stall be caused by poor instrumentation? The crystals were checked before and after each major run; at no time was there any trouble with them. No shorts. No grounds. No broken leads. The crystals picked up a constant tone after the runs as well as before. With no

[illegible][illegible]

external amplifier, an approximate sine wave and random noise were obtained. With the same gain, the deflection produced by the random noise was greater than the deflection produced by a human being holding the leads. The deflections caused by the human being were 60 cycles, although he was not in immediate contact with any source of power.

Concerning the run, described in the Procedure, which was made with the blades placed upon the crystals, there was no noticeable change in the oscilloscope patterns. If anything occurred, it was merely a rounding of the highest deflections. When a blade was centered directly over a crystal, the crystal was still partially in the passage. It was concluded that partial covering of the crystals had negligible results on the oscilloscope patterns.

When the exhaust valve was closed slowly, the only effect was to increase the compressor's pressure ratio until it surged. Nothing unusual occurred to the oscilloscope patterns or to the tufts.

The tufts gave every indication that was expected of them including the surge of the air compressor. (This surge was very low in frequency, approximately $1\frac{1}{2}$ cycles per second.)

Therefore, the authors don't believe it was

entirely sufficient for the purpose of the work and which will
 be sufficient. With the same type, the collection prepared by
 the various authors was found to be the collection prepared by a
 single hand, taking the same. The collection of the
 books being made to appear, although no one was in the field
 except with the interest of the work.

...the same the work, the same in the present
 which was made with the same plan as the original, there
 was no noticeable change in the handwriting. It appears
 to be the same as the original of the original collection,
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 appears as the original and appears to be the original
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 one to be found. The handwriting of the original was found to
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 hand of the original of the original of the original. (This copy was
 very low in number, as compared to the original of the original.)

Therefore, the original of the original of the original is the

instrumentation.

If the foregoing is true -- and the authors sincerely believe it is -- then the answer must be sought elsewhere.

Analytically, there may be a lack or error in the theory. The authors don't believe there is anything wrong with the theory as far as it goes, but there is more to the theory than has been expounded. It has been suggested that the dynamics of rotation must enter. This is disqualified quickly by the British in Ref. 5, wherein rotating stall was obtained in a stationary diffuser.

It appears that the phenomenon of rotating stall has the attributes of a self-excited but damped vibration of classical mechanics. The energy source is present in the air stream. By analogy, the air contains the damping force and the spring force. The authors think that the unstable region of a gentle C_L - α curve as shown in Fig. 14a would assist in starting rotating stall. A decrease in the effective damping force would occur since there would be little energy dissipated by the damping force until the stalled region had grown.

There must be some instability connected with rotating stall. Anything to increase that instability should aid in starting rotating stall.

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It has been stated that the variables investigated by the authors were mass flow, velocity, pressure, solidity factor, angle of attack and blade form. These variables were not all altered individually; i. e., mass flow was varied, but other parameters such as velocity and pressure changed at the same time. This procedure was followed for two reasons:

- (1) Time limitations prevented the altering of individual factors, if the entire field was to be surveyed.
- (2) By accomplishing the outlined variations, it was hoped that the magic factor or combination of factors would be discovered. Then further investigation of this factor or group of factors could be undertaken.

The very method used suggests that the problem of rotating stall may be amenable to dimensional analysis. By Buckingham's method, the parameters used by the authors could be non-dimensionalized. (The blade form parameter should be enlarged to include length, thickness, $C_{l-\infty}$ curves, and size and length of the passage between blades.) By experimentation, the unimportant non-dimensional factors could be eliminated.

Further experiments on important factors could then proceed more successfully.

Empirically, it is believed that there are two excellent channels open for further investigation:

(1) Make new guide vanes for this set-up.

The failure to produce rotating stall has not in the past been due to a lack of some factor in the present theory. The the flow angle. Then by putting flat plates in the diffuser at the proper incidence angle, the leading edge of one plate would be out of the stalled region of the preceding plate. This study would

show a better comparison between the two C_L - α curves, as discussed above.

(2) Last -- and most important! Set up the

conditions encountered in Ref. 5, where-

in a rotating stall was inadvertently pro-

duced and was not further investigated.

Since this was a centrifugal diffuser, much valuable information should be ob-

tainable from such a study, especially

when compared with other present day experiments.

Dr. J. H. R.

Further experiments are necessary to determine the effect of the

temperature of the medium on the rate of growth.

Consequently, it is necessary to determine the effect of the

medium on the rate of growth of the organism.

(2) It is also necessary to determine the effect of the

medium on the rate of growth of the organism.

the flow angle. Then by putting the

plates in the holder at the proper in-

termediate angle, the desired angle of the

plate would be out of the stated region

of the preceding film. This study would

show a better comparison between the

two C - curves in the same film.

(3) Last -- and most important -- set up the

conditions encountered in the 2, where-

in a vertical still was investigated by-

using the same and known investigation.

There was a horizontal film.

Some vertical film was also set up.

Results show that a study regarding

the subject of the film is

V. CONCLUSIONS AND RECOMMENDATIONS

No rotating stall was encountered at any of the conditions investigated. These conditions included varying pressure, mass flow, velocity, blade form, solidity factor and angle of attack. The failure to produce rotating stall lies not in the set-up, but rather in a lack of some factor in the present theory. The lacking factor is not the dynamics of rotation.

The lack may be that a larger unstable operating region of the effective $\zeta-\infty$ curve is needed. An analogy along this line can be made with self-excited vibrations in classical mechanics. Vol. III, War Emergency Series Monograph 1, page 411.

A strong recommendation is made by the authors to apply the methods of Buckingham's dimensional analysis to the problem of rotating stall.

Two experimental fields for farther study should be:

- (1) Increase the cascade flow angle when the flat plates are used. This will make the stalled region of one blade miss the leading edge of the adjacent blade.
- (2) Reproduce and study the rotating stall produced in a stationary diffuser by the British in Ref. 5.

—you will be very disappointed when this printer will

different investment, their conditions include varying degrees

more than velocity, state forms velocity tables and graphs at

Source: The author is grateful to the following for their assistance:

and control is a part of good design. The

leading factor is not the dynamic of relations

The last way to test a target variable against a set

There is no doubt that the results of the study are of great importance for the development of the theory of the origin of the universe.

—(continued from page 10)

1992

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not to anyone, including a "straggler" in a room with glass

State gallery is under way

Two experimental diets are further shown in

111. Show that the maximum flow equals the value of the flow.

add name New old? .how are things with

—continued from page 10—

ing edge of the adjacent plate.

(2) Experience and study the rotating staff

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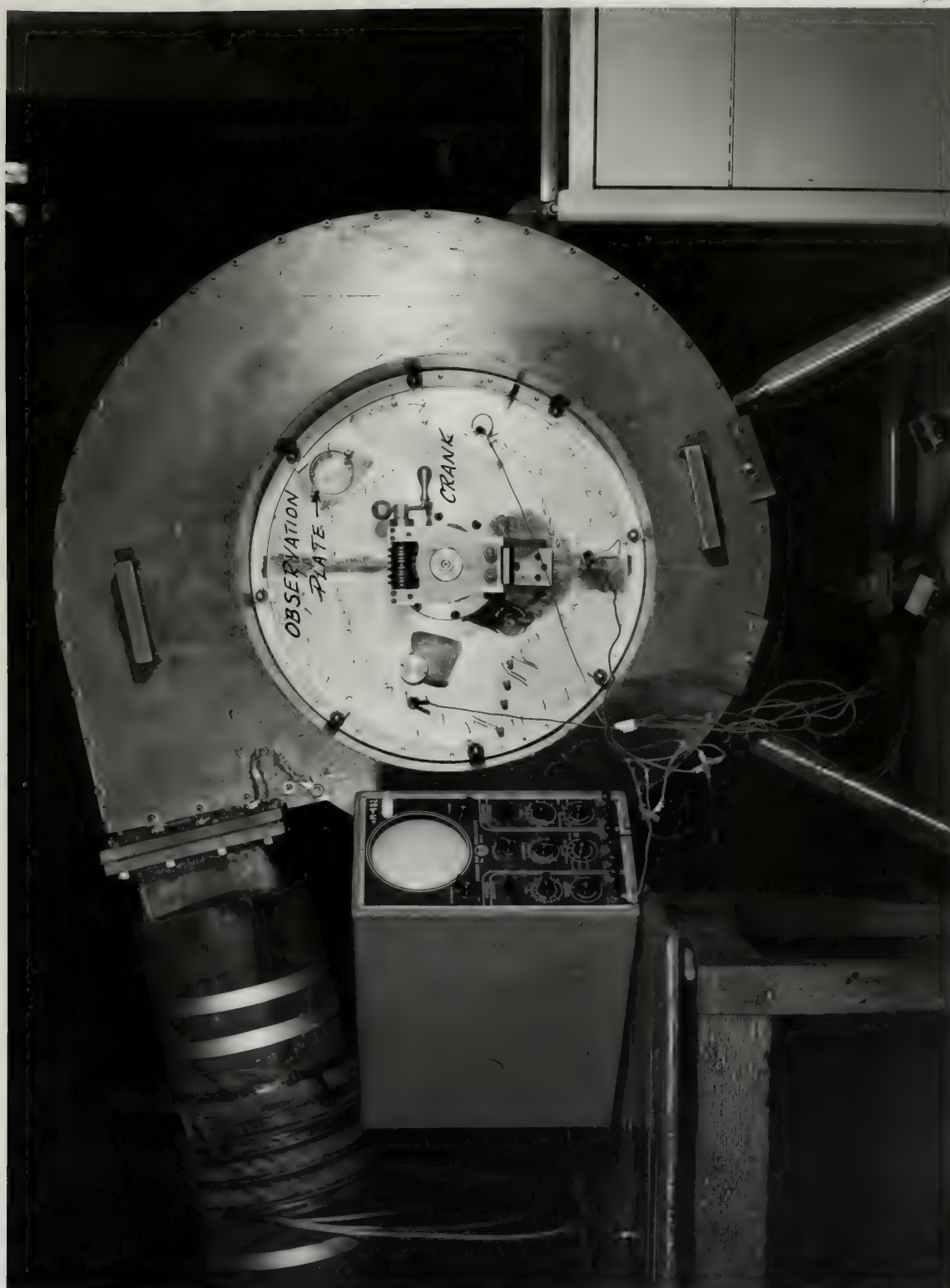
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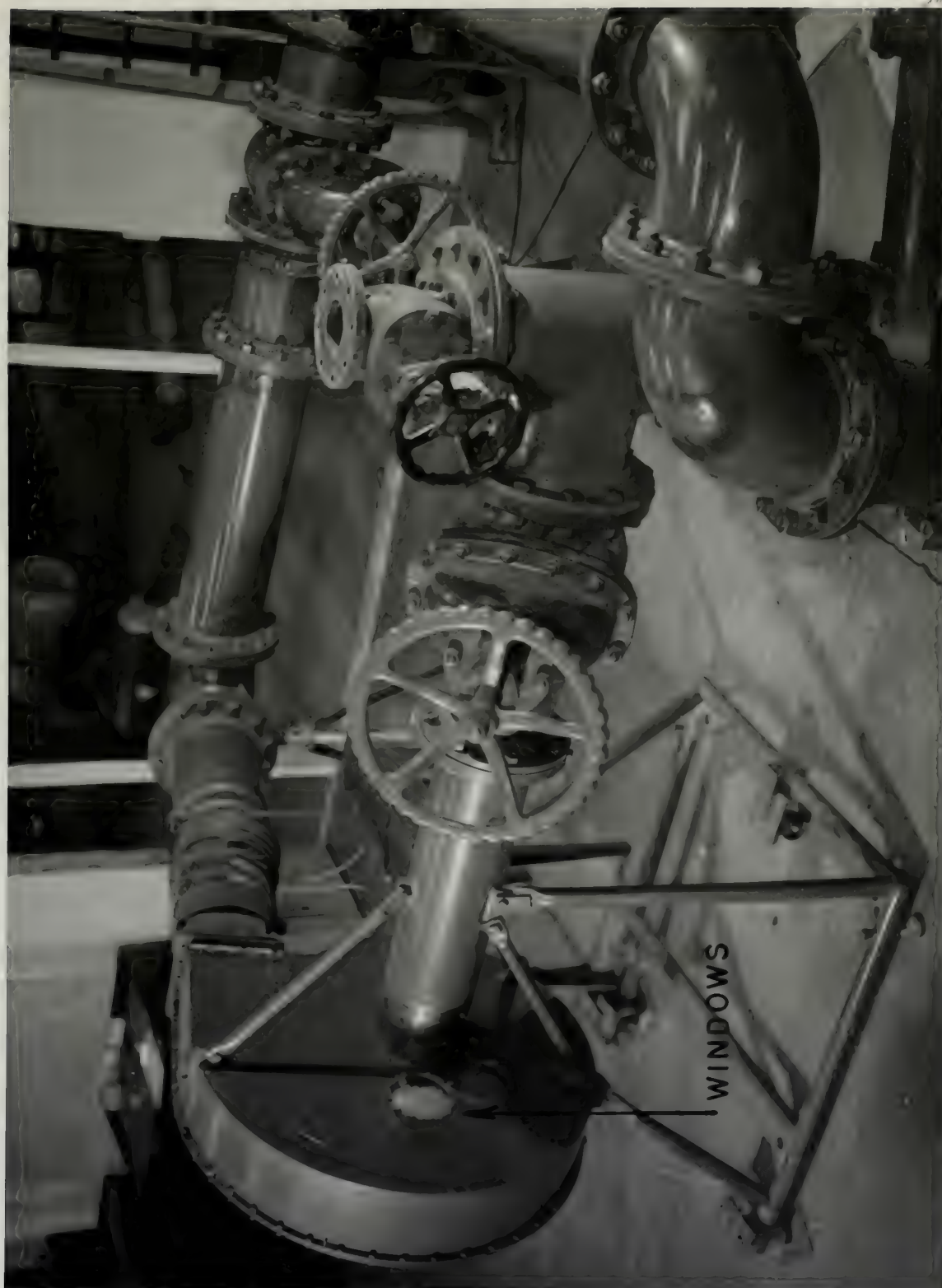
Table I

DESIRED OPERATING POINTS

POINTS	$P_r = \frac{p_{o2}}{p_{o1}}$	π_{mi}	MFF
1	1.18	0.175	0.060
2	1.50	0.287	0.170
3	1.90	0.375	0.240
4	2.20	0.418	0.300
5	2.30	0.460	0.550
6	3.00	0.495	0.450
7	3.30	0.516	0.500
8	1.75	0.490	0.875
9	2.10	0.395	0.230



TEST SET-UP (FRONT VIEW)
FIG. 1



TEST SET-UP (SIDE VIEW)
FIG. 2



NOZZLE BLADES
FIG. 3



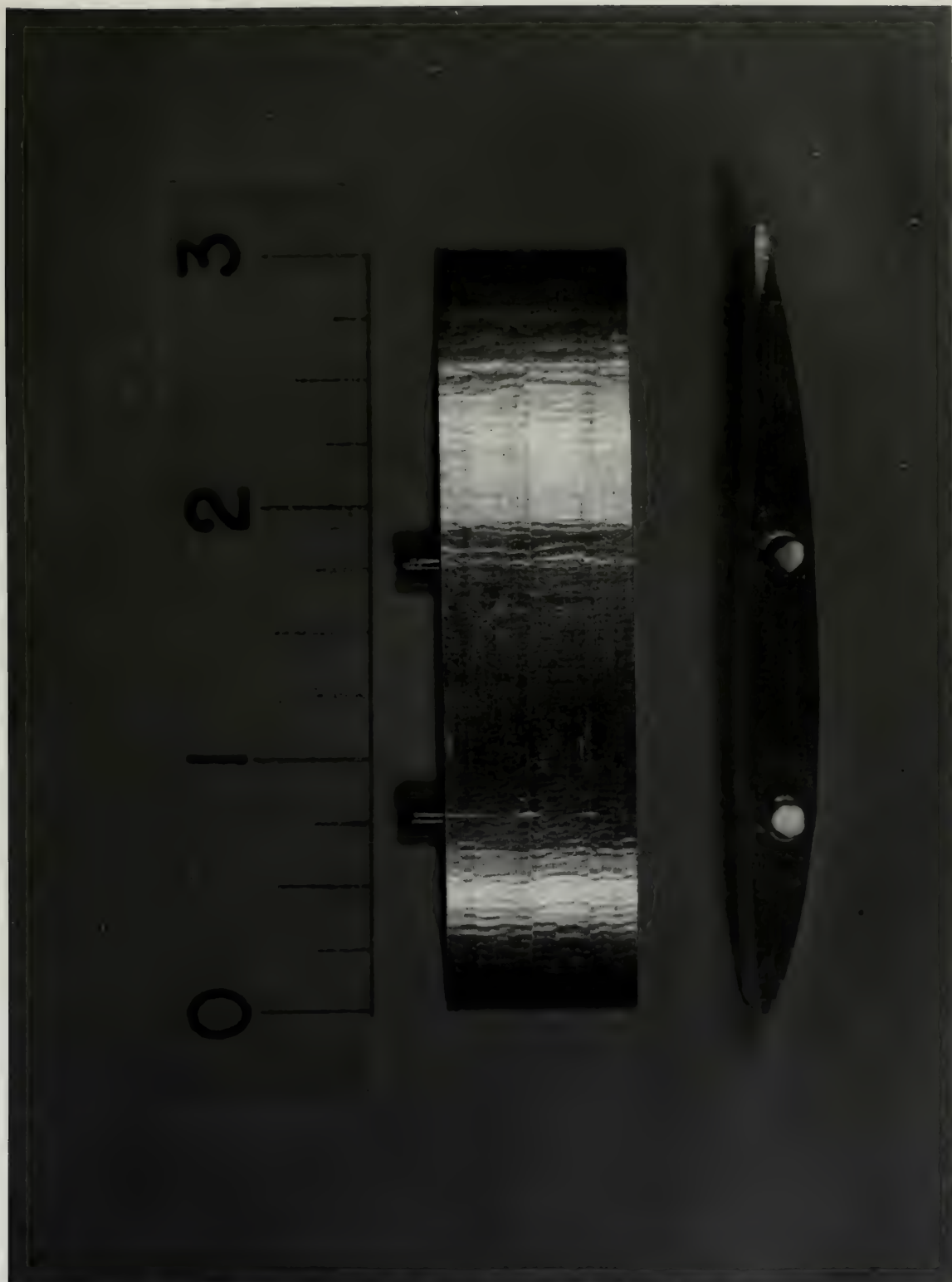
TEST SET-UP (OUTER COVER REMOVED)
FIG. 4



BLADE RING REMOVED
FIG. 5



C-14 BLADES
FIG. 6



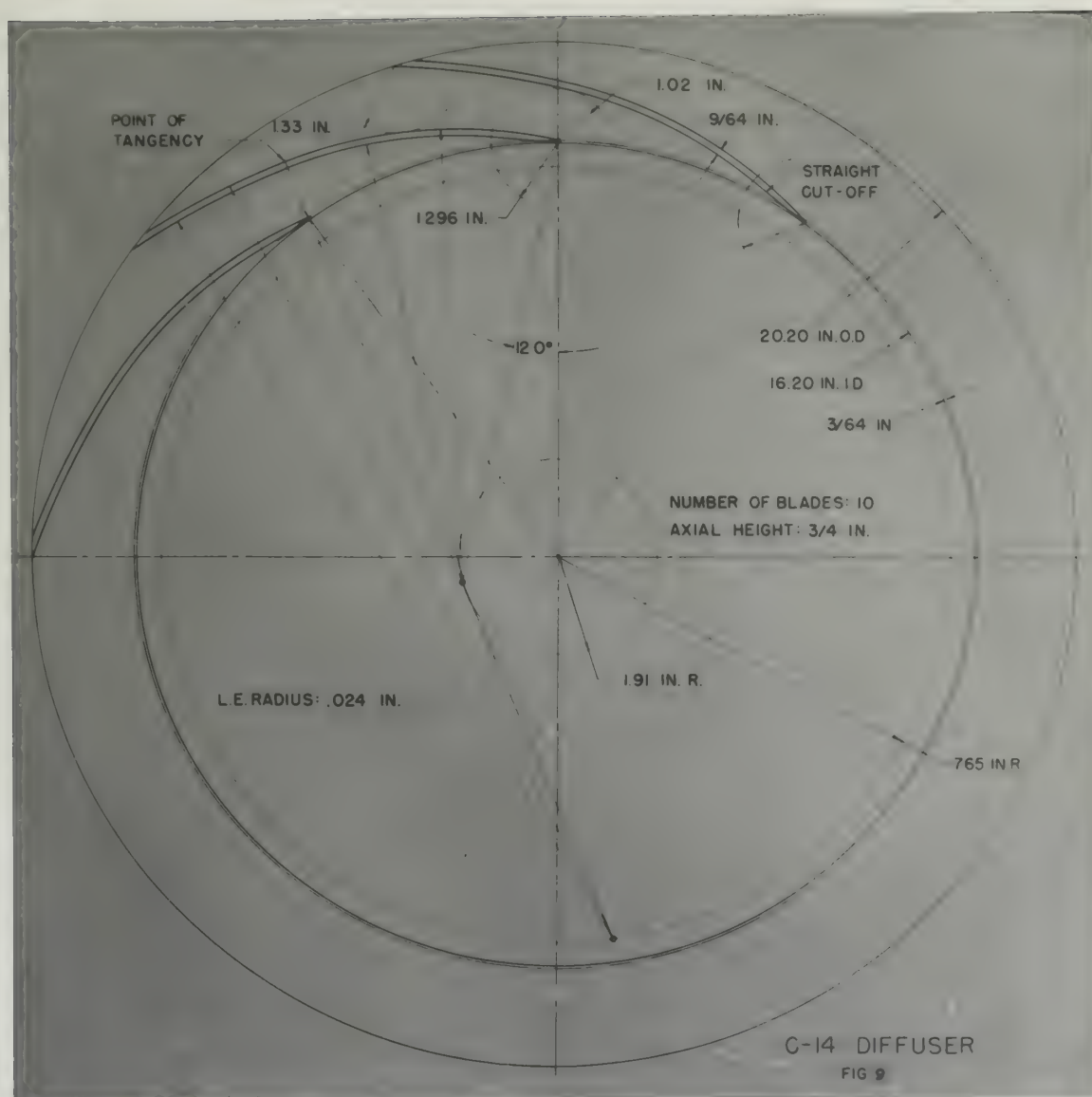
TRANSFORMED NACA 65-(12)10 BLADES
FIG. 7



FLAT PLATES
FIG. 8

DETAILS OF THE C-14 DIFFUSER

BLADES



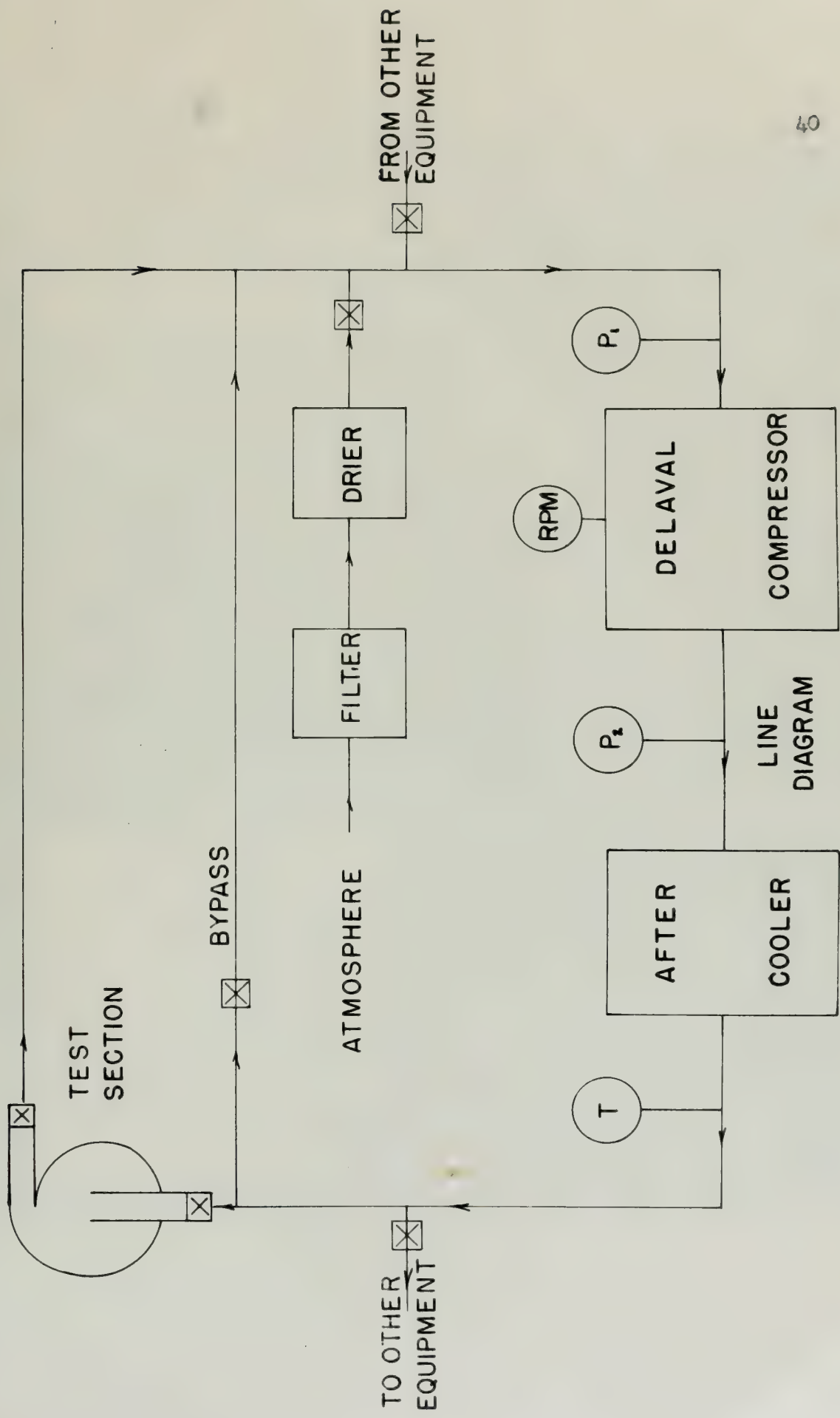
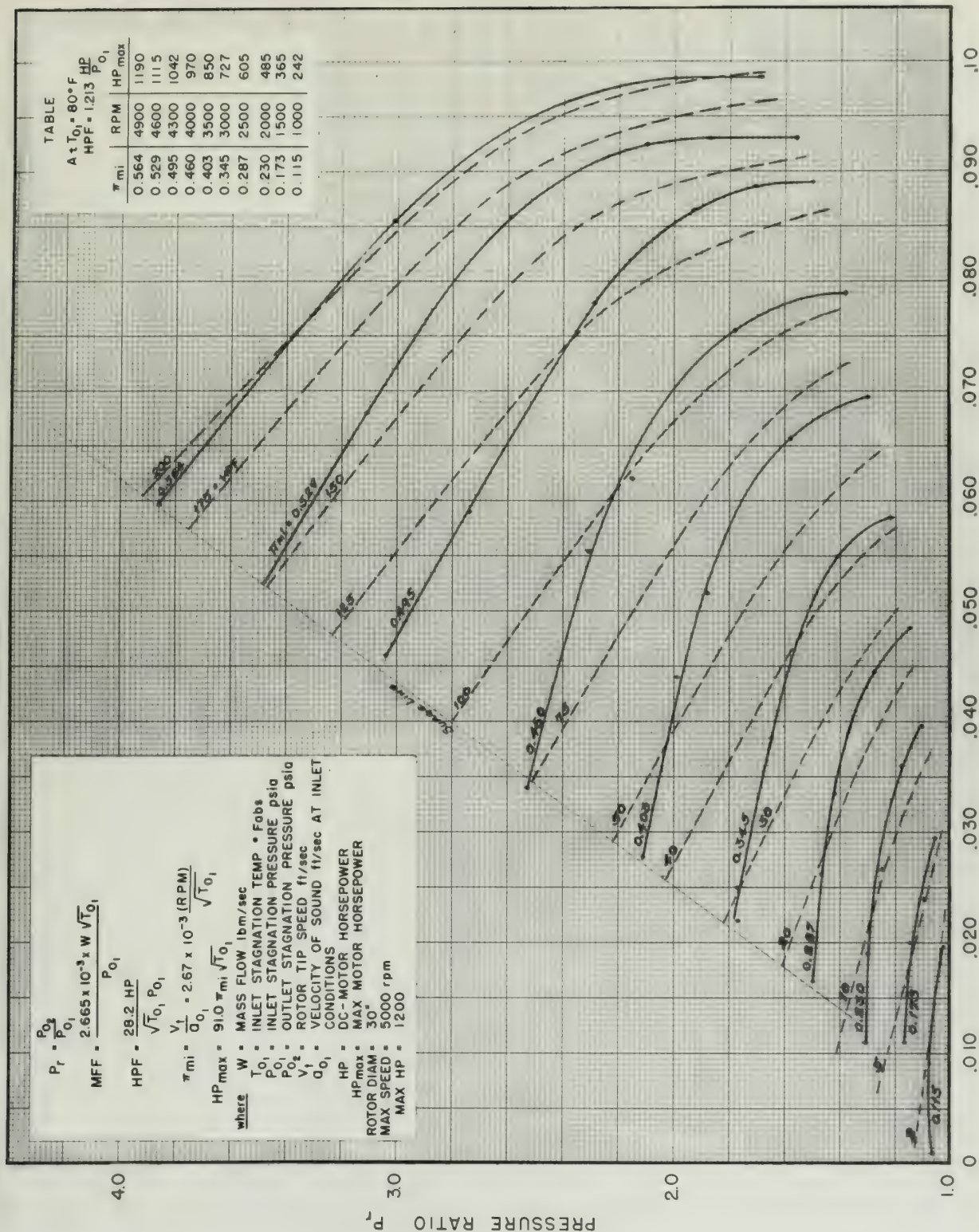


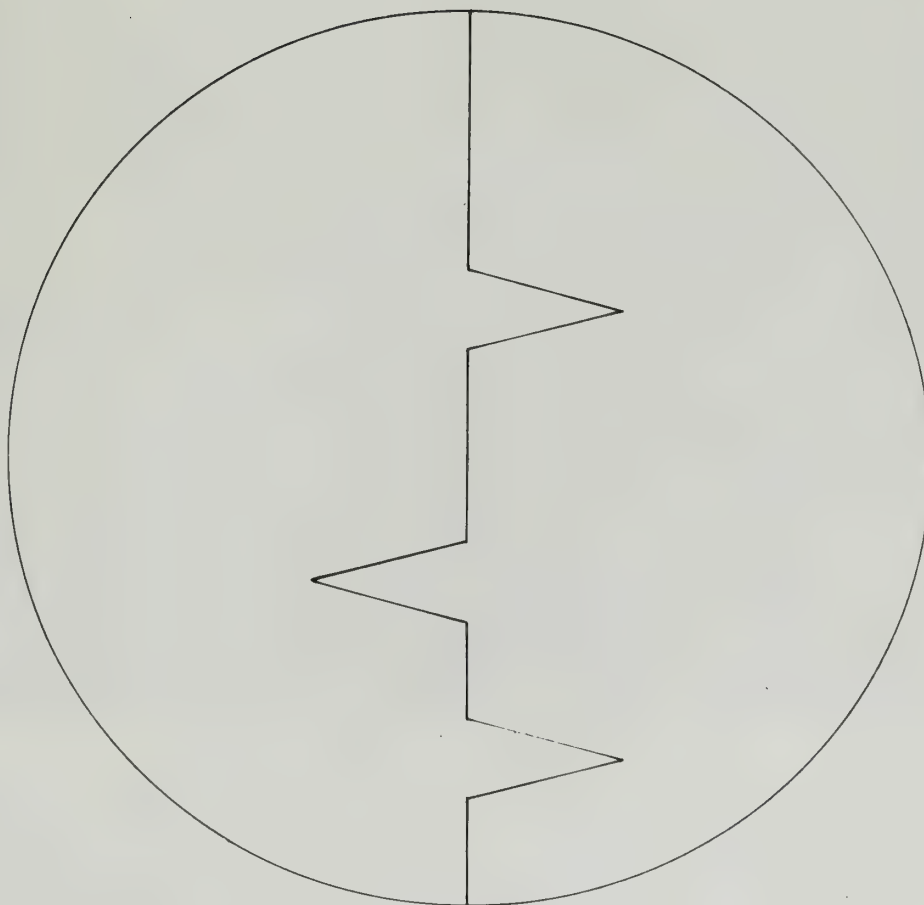
FIG. 10

MIT GAS TURBINE LABORATORY - WIND TUNNEL DeLAVAL COMPRESSOR CHARACTERISTICS

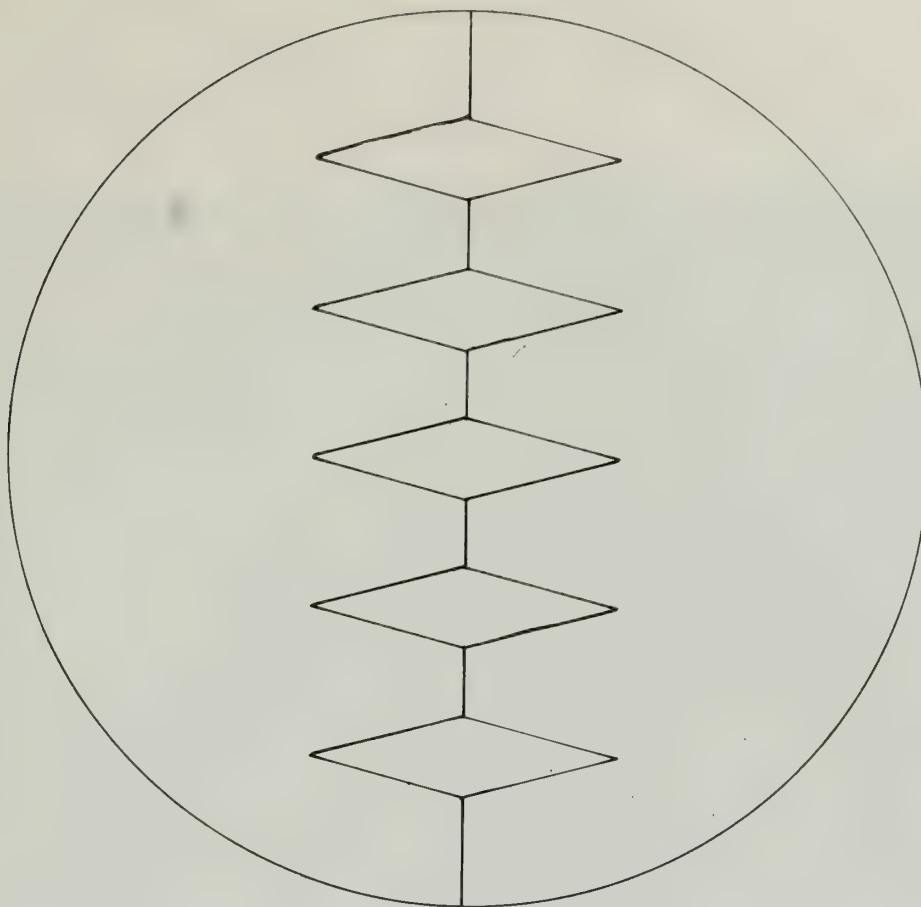


MFF - MASS FLOW FACTOR
FIG. 11

a
ROTATING STALL



b
SURGE

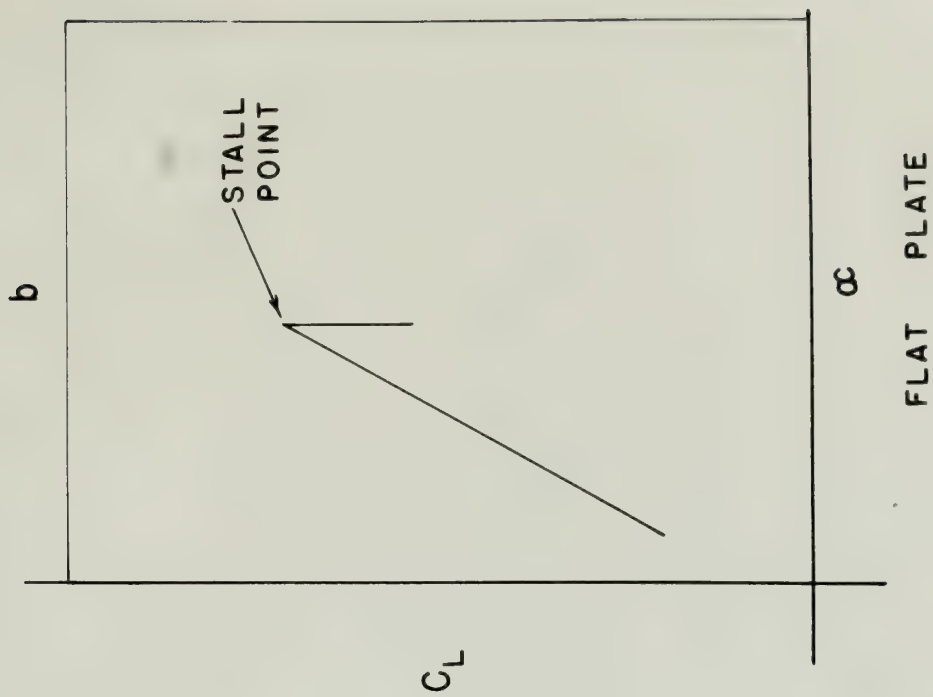
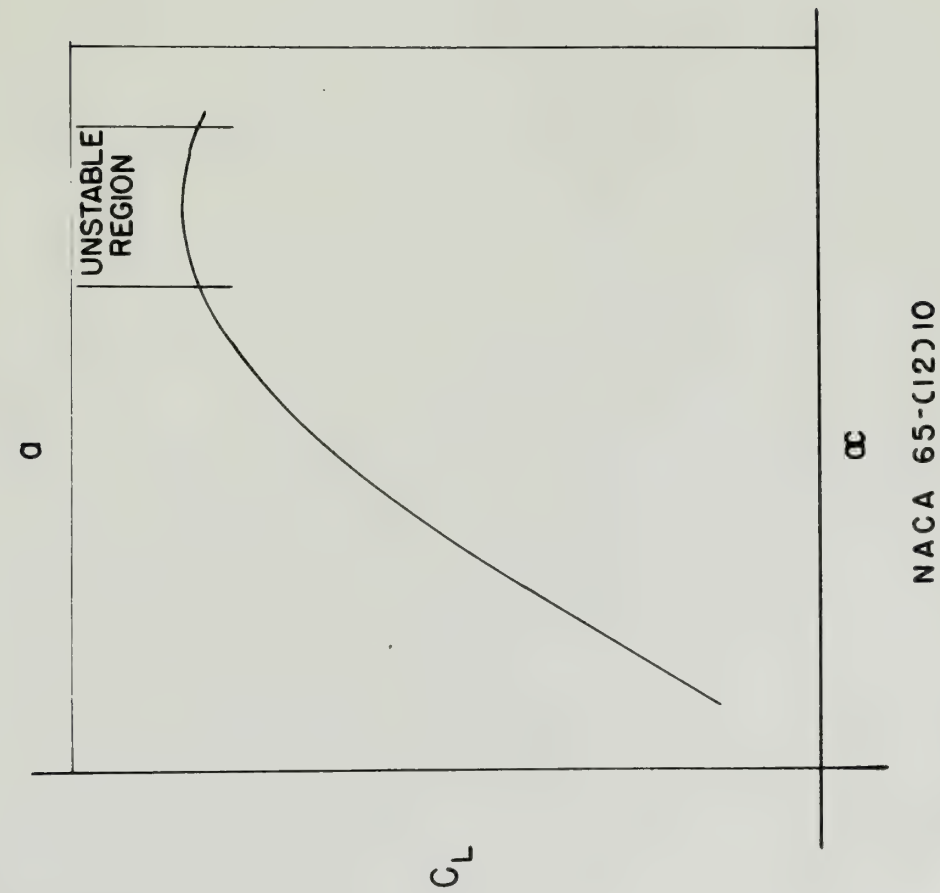


OSCILLOSCOPE PATTERNS

FIG. 12

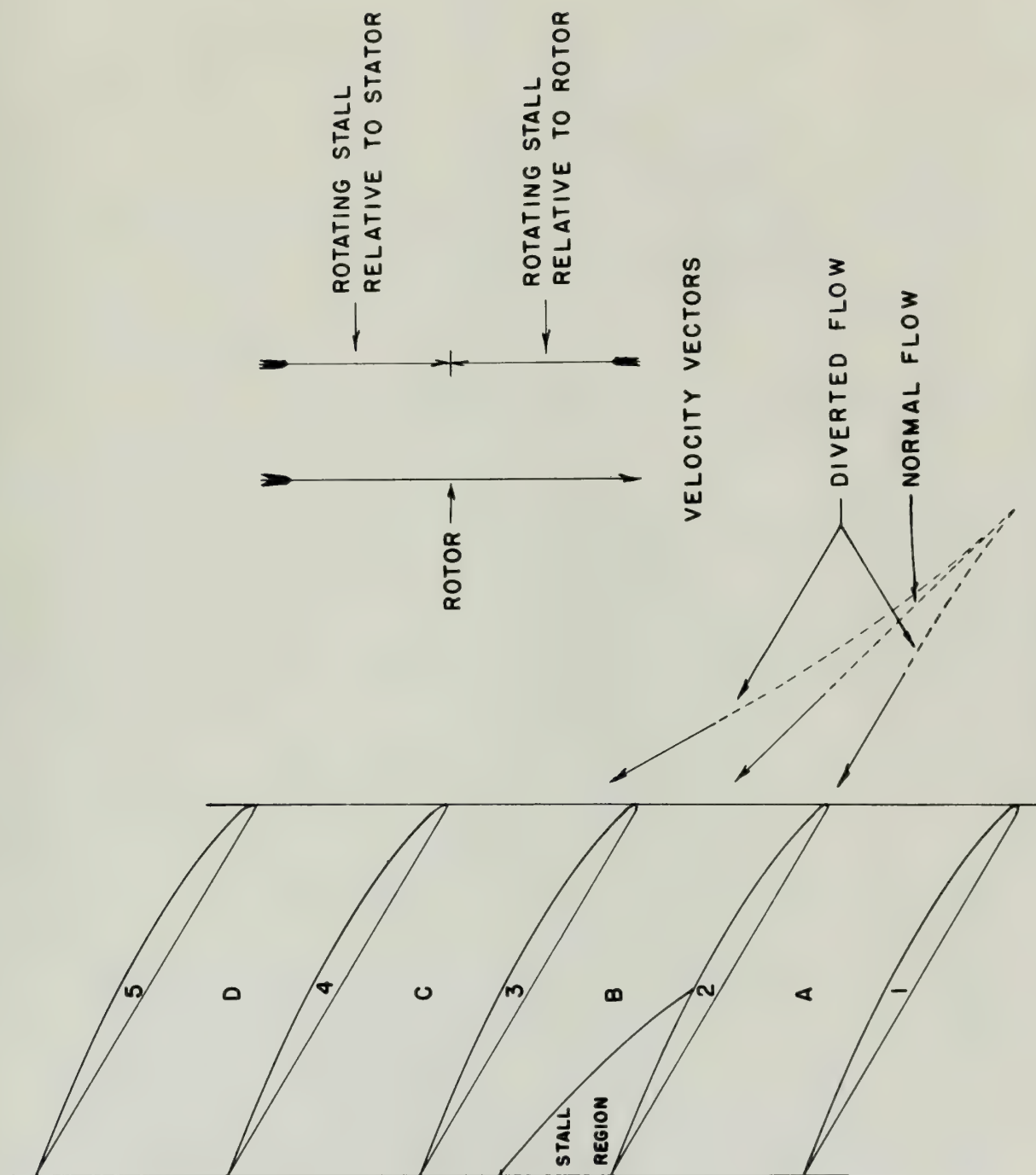


OBSERVATION PLATE WITH TUFTS
FIG. 13



BLADE CHARACTERISTICS

FIG. 14



ROTATING STALL THEORY

FIG.15

III Appendix A Details of the Diffuser Test Section

DETAILS OF THE DIFFUSER TEST SECTION

The diffuser test section is mounted in a collector manifold as shown in Fig. 1 of the thesis. It is supported by the cover plate and the inlet guide vanes as shown in Fig. A-1, of this Appendix.

To disassemble the test section the following steps

are required:

- (1) Remove the gearing mechanism as shown in Fig. A-1.
- (2) Remove the hold-down lugs around the cover plate.
- (3) Remove the cover plate.
- (4) Remove the test section.

To remove the blade ring, turn the test section to a vertical position. Located on the back of the section are allenhead screws which hold the blade ring to the test section. After removing the screws, the blade ring can be forced out by inserting a drift into the screw holes. To assemble and remount the test section, the reverse of the above procedure is followed.

In order to rotate the test section the following

procedure should be performed:

Appendix A

DETAILS OF THE ELECTRIC TEST SECTION

The electric test section is mounted on a collector assembly as shown in Fig. 1 of the manual. It is supported by the cover plate and the base plate which are shown in Figs. A-1 and A-2.

To disassemble the test section the following steps are required:

(1) Remove the testing mechanism as

shown in Fig. A-1.

(2) Remove the hold-down pins around the

cover plate.

(3) Remove the cover plate.

(4) Remove the test section.

To remove the blade stud from the test section as a vertical position. Located on the back of the section are alignment screws which hold the blade stud in the test section. After removing the screws, the blade stud can be turned out by inserting a screwdriver into the screw holes. To assemble and remove the test section, the reverse of the above procedure is followed.

In order to rotate the test section the following

procedure should be performed:

- (1) Turn the bronze thrust nut on the gearing mechanism clockwise to release the test section from the cover plate.
- (2) Turn the crank, located on the gearing mechanism as shown in Fig. A-1. This will turn the test section to any desired position.
- (3) To lock the test section in the desired position, turn the bronze thrust nut counterclockwise until the test section is flush against the cover plate. This anchors the blades firmly, preventing flutter.

In order to change the angle of flow it is necessary to rotate the nozzle blades. This is accomplished as follows:

- (1) Roughly align the nozzle blade angle indicating marks, located on the back of the test section, with the scribed line on the upper window of the two plexiglass windows. These windows are located on the back of the collector manifold, as shown in Fig. 2 of the thesis.
- (2) Lock the nozzle blade turning ring. This

(1) Turn the crank a thrust nut on the bearing

mechanism clockwise to release the test

section from the cover plate.

(2) Turn the crank, located on the bearing

mechanism as shown in Fig. 4-1. This

will turn the test section to any desired

(3) The test section is now in the desired

position, turn the crank a thrust nut on the

clockwise until the test section is flush

against the cover plate. This anchors the

test section in the bearing mechanism.

In order to remove the test section it is necessary to

rotate the test section 180 degrees. This is accomplished as follows:

(4) Rotate the test section 180 degrees by turning

the crank, located on the back of the

test section, until the section line on the

upper window of the test plate line win-

dows. These windows are located on the

back of the test section, as shown

in Fig. 5 of the thesis.

(5) Lock the test plate in the desired position. This

is done by turning the round-head screw, (located in one of the plexiglass mounting screw holes), into a hole that should be almost in line with the screw. The test section may have to be moved slightly to insert the screw properly.

- (3) To rotate the nozzle blades turn the gearing mechanism located on the cover plate. By aligning the indicating marks the flow angle is determined. The middle position gives an angle of flow of 15 degrees, the upper position 20 degrees and the lower position 10 degrees.

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Appendix B

CONFORMAL TRANSFORMATION OF NACA 65-(12) 10 BLADES

Ref. 5 of the thesis gives the background, theory, and development of conformal transformation as applied to cascades. This Appendix will show the step by step process of the conformal transformation, by means of a sample calculation. The point chosen is the 50% chord station of the upper surface.

NACA Report 824 by Abbott and Von Doenhoff gives the coordinates of the camber line and standard thickness form for this blade. The upper surface, 50% chord position is found by adding the mean camber ordinate, 6.618, to the basic thickness, 4.812, at this point. The result is that the ordinate is 11.43 at station 50, both numbers in per cent chord. Fig. B-1a of this Appendix shows this point plotted on the $x' - y'$ axes. These $x' - y'$ axes are at a 14.1 degree angle of attack. The reason for this angle of attack is discussed in the thesis proper.

In order to use the conformal transformation formulae as developed in Ref. 5, it is necessary to obtain the coordinates of all points referred to the $x - y$ axes of Fig. B-1a. From Fig. B-1a it can be seen that:

Appendix B

CONFORMAL TRANSFORMATION OF WALK 44-111 IN ALIEN

Fig. 1 of the report from the Department, 1947.

and development of conformal transformation as applied to con-
formal. This Appendix will show the steps by which the con-

formal transformation, by means of a simple calculation. The

point chosen is the 100' point station of the upper station.

WADA Report 100 by 100' and 100' (100' gives

the coordinates of the center 100 and around 100' from the

100' point. The upper station, 100' point station is found by 100'

for the lower station, 100', in the lower station, 100'

of this point. The result is that the station is 100' at station 100.

100' station is put into 100'. 100' is at this station, 100'

100' point station is 100' at 100'. There is a 100' at 100'.

100' station is at 100'. The reason for this is that it

discussed in the first paper.

In order to use the conformal transformation for-

station as developed in Fig. 1, it is necessary to obtain the 100'

station of all points relative to the 100' station of Fig. 1-100. 100'

Fig. 1-100 it can be seen that:

The coordinates of the point $x = x' \cos \alpha + y' \sin \alpha$

and the coordinates of the point $y = y' \cos \alpha - x' \sin \alpha$

Applying these equations to the point being considered, shows that:

$$x = (50.000) (\cos 14.1^\circ) + (11.430) (\sin 14.1^\circ) \\ = 51.27812$$

$$y = (11.430) (\cos 14.1^\circ) - (50.000) (\sin 14.1^\circ) \\ = -1.09511$$

For the conformal transformation from rectangular coordinates to circular coordinates such as Fig. B-1b, the author of Ref. 5, on page 10, arrives at the following equations:

$$1) \quad R = \frac{r_2}{r_1} = e^{\left(\frac{m y - x}{m^2 + 1} \right)} \\ 2) \quad \Theta = \frac{m y + x}{m^2 + 1}$$

where: r_2 = final radius

r_1 = initial radius

$$e = 2.71828$$

$$m = \tan \beta$$

x, y = rectangular coordinates

Θ = circular coordinate (radians)

β = angle of logarithmic spiral with

tangential direction.

β in the present case is 15° , while $r_1 = 8.1$ inches.

$$x = x' \cos \alpha + y' \sin \alpha$$

$$y = y' \cos \alpha - x' \sin \alpha$$

Substituting these equations in the polar form equation

shows that:

$$r = \frac{1}{1 - \cos \alpha} \quad \text{or} \quad r = \frac{1}{1 + \cos \alpha}$$

$$r = \frac{1}{1 - \cos \alpha} = \frac{1}{1 - \frac{1}{2}} = 2$$

$$r = \frac{1}{1 + \cos \alpha} = \frac{1}{1 + \frac{1}{2}} = \frac{2}{3}$$

$$r = \frac{1}{1 - \cos \alpha} = \frac{1}{1 - \frac{1}{2}} = 2$$

For the conic section, the polar form equation is

$$r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

of the ellipse, we have the following equations:

$$1) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$2) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$3) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$4) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$5) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$6) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$7) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$8) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$9) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

$$10) \quad r = \frac{ep}{1 - e \cos \alpha} \quad \text{or} \quad r = \frac{ep}{1 + e \cos \alpha}$$

For the ellipse, we have the following equations:

The authors of the thesis knew they wanted the final blade to extend outward radially a distance of 1.4 inches. This set

$$R = \frac{r_2}{r_1} = \frac{8.1 + 1.4}{8.1} = 1.17283.$$

Then knowing $m = 0.26795$, and $m^2 + 1 = 1.07180$,

$$\text{as shown for } 1.17283 = \frac{\left(\frac{mx-y}{1.07180}\right)}{1.17283} = 1$$

or at station 100,

$$1) \quad K(mx-y) = 0.17875$$

The values of x and y at station 100 are found in the same way as x and y for the 50% chord station. When the station 100 values of x and y are substituted into equation 1), the result is a factor, K , needed for the radial distance desired. All values of x and y are then multiplied by this factor before substitution into equations 1) and 2). This factor, K , turned out to be 0.00339131.

Then for the 50% upper chord station,

$$\begin{aligned} r_2 &= (8.1) e^{\left(\frac{mx-y}{m^2+1}\right)(0.0033913)} \\ &= (8.1) e^{\left[\frac{(0.26795)(51.278) - (-1.09511)}{1.07180}\right](0.0033913)} \\ &= 8.489 \text{ "} \end{aligned}$$

θ , in degrees, measured counter-clockwise from the leading edge of the blade is:

$$\begin{aligned} &\left(\frac{my+x}{m^2+1}\right)(0.0033913)(57.29578) \\ &= \left[\frac{(0.26795)(-1.09511) + 51.278}{1.07180}\right](0.0033913)(57.29578) \\ &= 9.9068 \text{ degrees.} \end{aligned}$$

outward (usually a distance of 4 in. or more). This will

$$\text{Average } \bar{x} = \frac{21 + 18}{10} = \frac{39}{10} = 3.9$$

[illegible]

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$$(EIP E 00.0) \left(\frac{u - xM}{1 + xM} \right) \quad 2(1.8) = 3.7$$

$$(198500.0) \left[\frac{(11290.1) - (0.5512)(21525.0)}{1.0140} \right] \quad 9(18) =$$

858

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$$f(x) = 1.5x^2 + 2x - 1 \quad \left(\frac{dx}{dt} = 0 \right) \quad \left(\frac{d^2x}{dt^2} = 0 \right)$$

$$= 8.2098 \text{ gph}$$

Therefore, in the circular cascade, the transformed point will have the coordinates:

$$r_2 = 8.489 \text{ inches}$$

$$\Theta = 9.997 \text{ degrees,}$$

as shown in Fig. B-1b.



RECTANGULAR COORDINATES FOR
CONFORMAL TRANSFORMATION

FIG. B-1b

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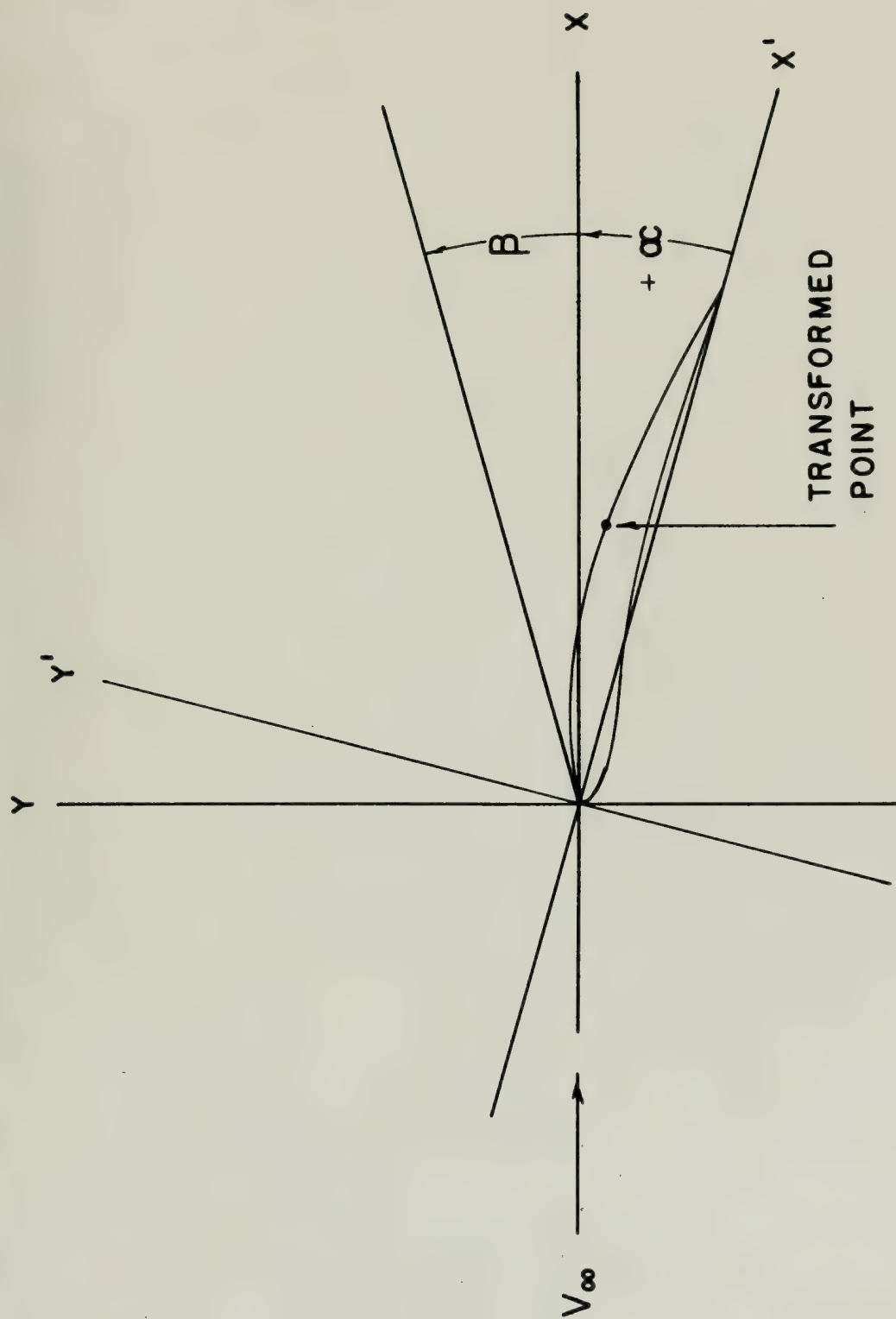
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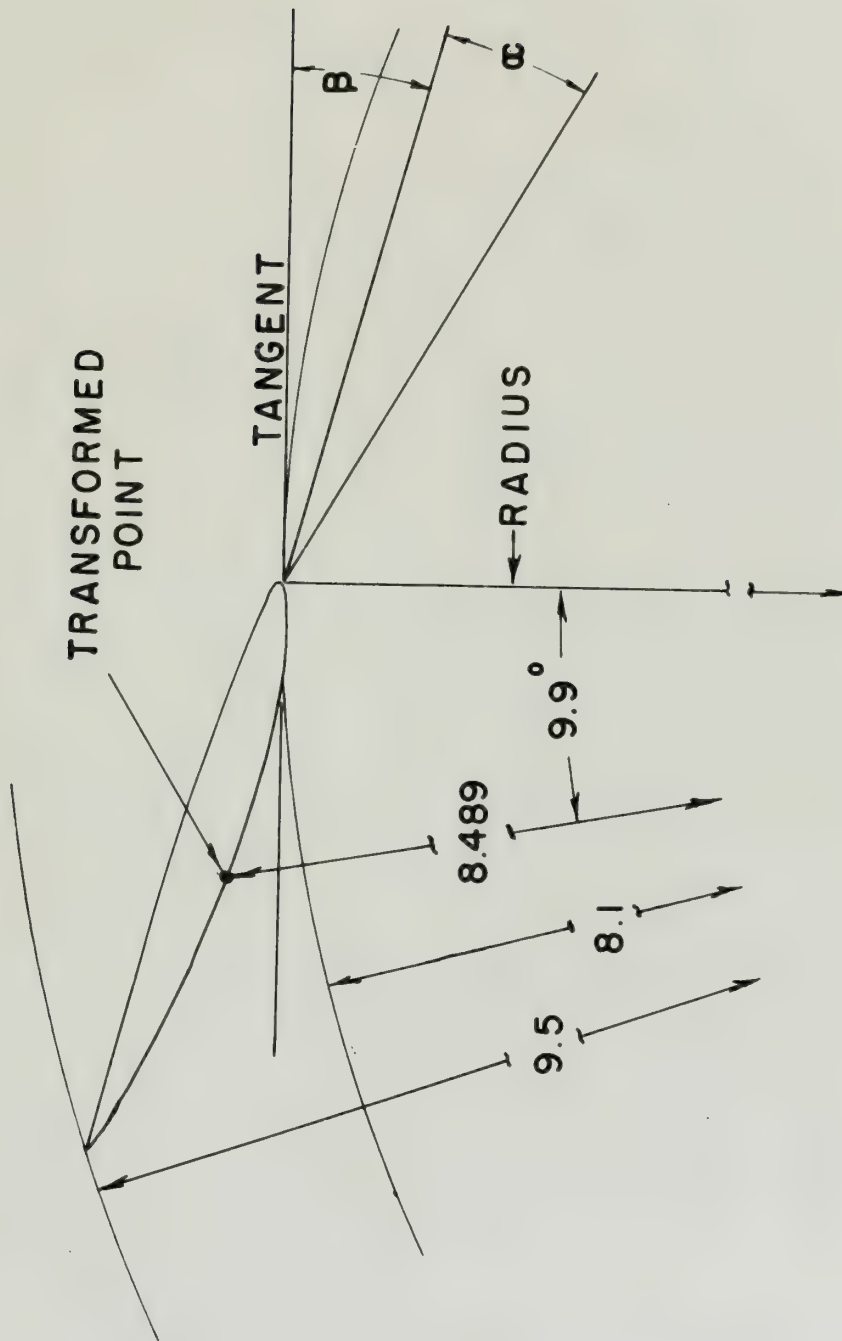
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RECTANGULAR COORDINATES FOR
CONFORMAL TRANSFORMATION

FIG. B-1a



CIRCULAR COORDINATES FOR
CONFORMAL TRANSFORMATION

FIG. B-1b

BARIUM TITANATE CRYSTALS

There was insufficient literature available to learn the capabilities and limitations of the barium titanate crystals which were available. In order to learn these capabilities and limitations, some experiments were undertaken.

One crystal was hooked to an oscilloscope. A quick check showed that the crystal was responsive to whistled or spoken noise, but insensitive to steady blowing. A variable speed electric motor was fitted with a stiff piece of cardboard. This cardboard was circular with a radius of seven inches. It had a one inch slot cut in one side. By placing a fan on one side of the cardboard and the crystal on the other, the range of sensitive frequencies of the crystals could be found. The speed of the cardboard disc was varied. The bottom frequency of response readable on the oscilloscope was approximately five cycles per second. Using musical tones, the crystals responded to 5000 cycles, and apparently would respond to higher frequencies.

Response to musical tones was sufficient proof that the crystals would respond to the changes in pressure due to stall, if that stall occurred faster than five cycles per second. Since

steady pressure measurements were not desired, but pressure fluctuations were, it was decided that these crystals would serve the thesis experiments very well.

After two months of use, some of the crystals started to lose their polarization. Repolarization of the crystals consisted of establishing 110 volts D. C. opposite polarity on each of the two leads, with a ground on the brass clip. The crystals were then heated to 265 degrees Fahrenheit, held there for fifteen minutes and then allowed to cool slowly with the voltage still applied.

Close calibration of the crystals is very difficult. For that reason, they are poor for quantitative measurements, although for qualitative pressure fluctuation measurements they are suitable. Because of their sensitivity, the crystals must be shielded and mounted securely in the test set-up.

Tests were made with the crystals in parallel and it was seen that there was no feedback discernible. Since the crystals could be selected for nearly the same sensitivity, when put in parallel, simultaneous pressure fluctuations on more than one crystal did not add on the oscilloscope. This is because the crystals generate an e. m. f. which is approximately equal.

as P₀₁ and Appendix D for the air flow.

The data were collected, and the operating point was determined.

OPERATING POINT CALCULATIONS

using the selected operating and by-pass valve to keep the flow

This procedure was followed in determining and

setting an operating point. Equations to be used are found on

Fig. 11 of the thesis. They are repeated here for convenience:

$$P_r = \frac{14.8 + 3}{14.8 - 6.8} = \frac{P_{02}}{P_{01}}$$

$$\pi_{m_i} = 2.67 \times 10^{-3} \frac{(RPM)}{\sqrt{T_{01}}}$$

The date of the selected run was May 12, 1954. The

operating point desired is number 4 of Table I of the thesis --

that is, $P_r = 2.20$; $\pi_{m_i} = 0.418$; MFP = 0.300. Barometric pressure was

30.27 inches of mercury, or 14.83 psia. Room temperature was

74°F. The readings taken were P_{01} (gage), P_{02} (gage), T_{01} , and RPM.

These readings are given in Table I of the thesis.

Following the method outlined in the Procedure Sec-

tion, the compressor was brought up to 3000 RPM. The atmos-

pheric inlet valve to the tunnel was closed.

When steady-state conditions were attained, the fol-

lowing readings were taken:

RPM = 3000, P_{02} = -0.3 psig, P_{01} = -6.8 psig, T_{01} = 650°F

at this point, MFP = 0.215

When steady-state conditions were attained, the fol-

lowing readings were taken:

RPM = 3000, P_{02} = -0.3 psig, P_{01} = -6.8 psig, T_{01} = 650°F

at this point, MFP = 0.215

When steady-state conditions were attained, the fol-

lowing readings were taken:

RPM = 3000, P_{02} = -0.3 psig, P_{01} = -6.8 psig, T_{01} = 650°F

at this point, MFP = 0.215

When steady-state conditions were attained, the fol-

lowing readings were taken:

RPM = 3000, P_{02} = -0.3 psig, P_{01} = -6.8 psig, T_{01} = 650°F

at this point, MFP = 0.215

WEAVING POINT CALCULATION

This section will discuss the calculation of the weaving point.

The weaving point is the point at which the two threads cross.

The weaving point is the point at which the two threads cross.

$$P = \frac{P_1}{P_2}$$

$$\pi_m = 2.67 \times 10^{-3} \frac{(RPM)}{\sqrt{t_0}}$$

The rate of the weaving is the rate at which the threads cross.

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The rate of the weaving is the rate at which the threads cross.

The rate of the weaving is the rate at which the threads cross.

$$P = \frac{14.8 - 0.3}{14.8 - 0.8} = 1.812$$

$$\pi_m = 2.67 \times 10^{-3} \frac{(3000)}{\sqrt{2+40}} = 0.320$$

as the point, the rate is 0.312

As P_r and π_{m_i} were low, the RPM was raised. As the RPM was increasing, the compressor started to surge. This surging necessitated opening the by-pass valve to keep the actual operating point below the surge line. Conditions steadied down at 3550 RPM. Then the following readings were taken:

$$\text{RPM} = 3550, \quad P_{o2} = 3.3 \text{ psig}, \quad P_{o1} = -6.7 \text{ psig}, \quad T_{o1} = 66^\circ\text{F}$$

$$P_r = \frac{14.8 + 3.3}{14.8 - 6.7} = 2.235$$

$$\pi_{m_i} = 2.67 \times 10^{-3} \frac{3550}{\sqrt{526}} = 0.415$$

Therefore, $\text{MFF} = 0.295$

These values of pressure ratio and mass flow factor were close enough to the desired operating point, to be within the arbitrary limits set in the thesis. These arbitrary limits were:

$$\text{Pressure ratio} = 0.05$$

$$\text{Mass Flow Factor} = 0.025$$

Conditions at the compressor control board were held at the desired operating point while a survey was made at the test section.

As T_1 and T_2 were low, the RTM was raised. As the flow was increased, the compressor started to surge. This surging was relieved by opening the bypass valve to keep the actual operating point below the surge line. Conditions remained about as follows. Thus the following readings were noted:

$$P_{01} = 21.1 \text{ psia}, \quad P_{02} = 1.1 \text{ psia}, \quad P_{03} = 0.1 \text{ psia}, \quad T_{01} = 51.7^\circ \text{F}$$

$$P_r = \frac{14.8 + 3.2}{14.8 - 0.7} = 2.532$$

$$T_{01} = 5.67 \times 10^{-2} \sqrt{\frac{3250}{250}} = 0.412$$

Therefore, $M_{01} = 0.293$

These values of pressure ratio and mass flow factor were close enough to the desired operating point, so the actual operating point was in the stable region. These values of M_{01} were

$$M_{01} = 0.293$$

$$\text{Mass flow factor} = 0.029$$

Conditions in the compressor control panel were kept at the desired operating point with a survey was made at the test

Thesis
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